THE UNIVERSITY OF ALBERTA

THE EFFECT OF ENVIRONMENTAL TEMPERATURES
ON TEMPERATURE AND MOISTURE CONTENT OF
DRY AND TOUGH WHEAT IN [illegible]

by

DAVID [illegible]

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

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DAVID BOAKYE AMPRATWUM

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Effect of Environmental Temperature on Temperature and Moisture Content of Dry and Tough Wheat In Unventilated Storage" submitted by David Boakye Ampratwum in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The principal objective of this project was to investigate how external atmospheric temperature affects the temperature and moisture content of bulk grain of different moisture contents in unventilated storage. Dry and tough wheat in unventilated storage were subjected to cooling and warming conditions - a simulation of the winter and spring temperature cycle. Grain temperatures over a cooling period of 28 days and a warming period of 35 days were collected and analyzed. The moisture contents and the condition of the wheat were determined at the beginning and end of the experiment. Analysis of variance, regression analysis, moisture determination and microbial analysis yielded the following results and conclusions:

1. Temperature differentials are established in grain under the influence of external temperatures. These differentials tend to stabilise under cooling conditions as the environmental temperature is approached. Under warming conditions microbial activity interferes with the temperature stabilization. The magnitude of the temperature differentials is affected significantly by time, depth from the surface of the grain, radial distance from the centre of the bin and moisture content of the grain.
2. Differences among the rates of cooling and warming at three radial spacings from the centre of the storage bin, between rates of cooling and warming at two horizontal levels and between rates of cooling and warming of dry and tough wheat were found to be significant.

3. Tough wheat cools more slowly than dry wheat. Tough wheat warms up more slowly than dry wheat when there is no microbial activity. Once microbial activity commences tough wheat heats more rapidly.
4. Above a grain temperature of about 60°F, fungi develop more readily in tough grain, leading to the creation of hot spots, than in dry grain.
5. Changes in temperature in bulk wheat are accompanied by moisture re-distribution.
6. Tough grain can become completely spoiled in a short period of time in the absence of a pronounced temperature rise.
7. Under the influence of external temperatures, the temperature of grain, Y, in unventilated storage and time, X, were found to be related by the regression equation as follows:

$$Y = a + bX + cX^2 + dX^3$$

where Y is in °F, X in days, a is a constant and b, c and d are multiple partial regression coefficients. The equation holds for both cooling and warming situations.

ACKNOWLEDGEMENT

The author would like to express his sincere thanks to those persons who contributed so greatly in the preparation of this thesis.

He is particularly indebted to his sponsors, the Canadian Commonwealth Scholarship Committee, for providing the opportunity of further study, and to his supervisor, Professor J.B. McQuitty, who has given the author his gracious assistance, guidance and encouragement not only academically but also socially. Grateful acknowledgement is made to Dean F.V. MacHardy, Professor H.P. Harrison and Professor T.A. Preston for their valuable assistance, advice and suggestions in this research program. The assistance of Dr. R.T. Hardin with the statistical content of the thesis, of Dr. A.J.F. Webster for the use of the Livestock Environmental Laboratory during the experiment, and of the technical staff of the Department of Animal Science, is sincerely appreciated. Grateful acknowledgement is also made to the Alberta Agricultural Research Trust for financial assistance towards the research project.

The technical assistance of Mr. E. Buehler, Mr. W. Sellers, Mr. R. Holowach and Mr. E.J. Moriarty of the Department of Agricultural Engineering and Mr. M. Mohyuddin of the Department of Plant Science is greatly appreciated. The many hours that his wife, Esther, spent in typing the first drafts of this thesis

are gratefully acknowledged. Sincere acknowledgement is also made to his fellow graduate students for their assistance and helpful suggestions, in particular to Mr. V.K. Agarwal and Mr. A. Aasen, and to Miss E. Symons for the final typing. The time, advice and moral support given by other members of the Department of Agricultural Engineering, and many others not mentioned above, are sincerely appreciated.

Without the help of all these people and health and strength from God, this thesis would not have been completed. Once again, thanks are given to all concerned.

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INTRODUCTION

Most farm products are stored before they are processed, marketed or consumed. Storage may mean a mere holding operation until the produce is either consumed or sold off the farm. At the other extreme, storage may involve complex handling and storage facilities in permanent structures. The storage period may consist of a few hours' or a few weeks' holding on the farm or in transit, or may extend to a year or more. Developments in mechanization have resulted in large quantities of cereal grain being harvested in a relatively short period of time. This has necessitated some form of storage on the farm.

The temperature at which grain is stored is one of the most important factors affecting its safe-keeping[9, 39]. It influences the moisture relationship between grain and air and the respiration rate of the grain. Snow[36] has pointed out that the rate of mold development depends on the relative humidity of the intergranular atmosphere in the stored grain. Williamson[40] has reported that the grain-moisture and air-moisture relationship varies with temperature. Cooling with cold air tends to lower the intergranular relative humidity and reduces the danger of fungal growth.

Temperature also influences the development of colonies of insect pests where these exist. Armstrong[2] has found that the saw-toothed grain beetle _Oryzaephilus surinamensis_, for instance,does not breed at temperatures below 65°F. Hyde[23] has reported that grain insects will not develop readily if the temperature is below 63°F and that the temperature at which fungal growth in grain is inhibited is much lower than that required for insect control. The actual temperature is a function of

the moisture content of the grain. The higher the moisture content of the grain, the lower the temperature must be to control effectively mold development. For moisture contents up to about 20-22%*, a temperature of about 40°F is necessary. At higher moisture levels,the temperature must be near freezing point to provide effective control of molds.

The harvesting of wheat in Westerm Canada begins in August and continues until the end of October. In unfavourable harvesting conditions, the period becomes prolonged. The respective normal daily mean temperatures for August, September and October in Edmonton, Alberta, are 60.0°F, 51.5°F and 42.2°F, in Calgary, Alberta; 59.2°F, 51.6°F, and 41.8°F, and in Lethbridge, Alberta; 63.3°F, 54.9°F and 45.3°F[28]. Most of the crop enters storage at ambient temperatures, or above the mean ambient temperature due to heating as a result of great mass, with a moisture content of 14.50% or less. This figure is the maximum safe moisture content for bulk storage of hard red spring wheat[7]. Due to unfavourable harvesting conditions in some years, such as 1968, grain with higher moisture content may require to be stored on the farm throughout the winter and longer. The surface of the storage is exposed to sub-zero temperatures from 3 to 5 months in winter resulting in condensation of moisture on the surface caused by convection currents inside the bulk[35].Fungus induced hot spots frequently develop as a result. When the hot spots reach temperatures higher than about 109°F heavy losses due to heating may occur[35,41].

Wheat, when introduced into storage, presumably will be at a uniform

* In this thesis all moisture contents are given on a wet-weight basis.

temperature, but the temperature distribution during storage will be influenced by the external temperature, and, in high moisture wheat, by heat generation from kernel respiration and microbial activity. Babbitt[5] used thermal constants to make an estimate of the effect of external changes on the temperature within dry wheat (9.20% moisture content, wet basis) stored in unventilated elevators. Williamson[40] has carried out a limited investigation into the temperature of grain harvested and stored on farms in central England, covering the treatment before storage and temperature changes during storage. He studied cooling by moving grain from bin to bin and by forced ventilation. Boyce[8] has worked on prediction of grain moisture and temperature changes at any point in a grain bed at any time, when drying is being carried out at a relatively rapid rate. A system of equations for predicting these changes was presented, methods of determining the relevant physical properties considered, and a step by step solution by means of a digital computor given. The computed results were in reasonable agreement with experimental observation.

Sinha and Wallace[35] have studied the ecology of a fungus induced hot spot in grain stored in Winnipeg, Manitoba. A hot spot in a 500 bushel experimental granary was initiated by the growth of Penicillium in damp wheat, 23% moisture content, during the five winter months when the temperature of the wheat ranged from 23°F to 47°F. The hot spot reached a maximum of 142.2°F. It cooled in 2 weeks and the cooling was attributed to inactivation of the fungi at high temperature,

progressive drying of the grain and spoilage of the appropriate medium for fungal growth.

There is, however, a lack of adequate information on how external atmospheric temperature affects the temperature and moisture content of bulk grain of different moisture contents in unventilated storage and how changes in the temperature of the external atmosphere affect hot spot occurrence. The project was initiated therefore to investigate the area with particular reference to dry and tough* grain.

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* According to the current grading system[31], cereal grain is divided into three categories on the basis of its moisture content. Dry grain is grain with a moisture content up to 14.50%. Tough grain is one with a moisture content between 14.50 and 17.00%. When the moisture content is above 17.00%, grain is graded damp.

OBJECTIVES

The project was carried out to determine the following:

1. The temperature differentials established in wheat grain under the influence of external temperatures.
2. The rate of cooling of the grain.
3. The rate of heating of the grain.
4. The distribution of hot spots.
5. The statistical significance of variation in temperature changes due to the influence of physical factors affecting grain temperature.
6. The distribution of moisture content after a specified period of storage.
7. The relative spoilage of the dry and tough grain after being subjected to cooling and warming.

LITERATURE REVIEW

Grain is hygroscopic and will gain or lose moisture under a given set of temperature and relative humidity conditions until equilibrium is attained. The moisture content of the grain influences its storage life. Thus temperature and moisture content are important factors in the storage of the grain.

Temperature

When wheat is placed in storage in a grain bin, it is subjected to any temperature changes taking place in the external atmosphere. The temperature of the wheat is influenced therefore by external temperature changes. Hall[19] has reported that the surface responds quickly to external temperature variations but the centre of the grain mass lags considerably. There are internal and external sources of heat which cause temperature changes to occur within the bulk of stored wheat. The internal sources of heat are respiration, fungal and bacterial activity, insect infestation and the heat of the product when placed in the bin.

The external sources of heat are due to the external atmosphere. They are caused by daily temperature fluctuations and seasonal changes in temperature influenced by location. The pattern of temperature variation of a mass of wheat over a period of time is very similar to that of temperature changes occurring in the earth's crust[25]. One would expect temperature changes corresponding to the daily variation of temperature from night to day and also much slower and greater variations due to the seasonal changes from summer to winter.

Babbitt[5] made estimates, from mathematical formulae, for variations in the temperature of wheat stored in unventilated grain elevators, by considering three types of temperature change. The following is a summary of the estimates:

1. The diurnal temperature variation corresponding to the difference in temperature between night and day.

   For a temperature change of 20°F from day to night, the grain temperature is changed 1°F at a depth of 5 inches. The effect of daily variations will therefore be scarcely noticeable below five inches.

2. The annual variation corresponding to the seasonal changes of temperature.

   The annual temperature variation of the grain at a depth of 13 ft. is never greater than 1°F. Conditions for Port Arthur, Ontario, were used for the estimation. The highest average temperature for a month is 73°F (July) and the lowest is -4°F (January and February).

3. The temperature change by which the temperature of the wheat slowly becomes equal to the mean temperature of the surroundings.

   At the end of one year period the temperature below 20 ft. from the surface has increased less than 1°F. Thus the temperature below 20 ft. is practically unchanged and the wheat remains at the temperature of storage. Babbitt considered a hypothetical case of a bin filled initially

with wheat at a temperature of 0°F and exposed on its upper surface to a temperature of 36°F. The upper temperature corresponds to the mean yearly temperature at Port Arthur.

In his estimations Babbitt considered the mass of wheat as a semi-infinite body bounded at the surface by the horizontal plane $x = 0$ and extending to infinity in the direction of x positive. He was concerned only with temperature changes in one direction, namely the vertical axis. In practice, the temperature changes are never confined to one dimension, but he argued that, in a centre bin of a grain elevator or a pile of wheat in a temporary storage where the lateral dimensions are large compared with the vertical, the temperature gradients in a horizontal direction are small and may be neglected.

Kelly[27] has pointed out the fact that the diurnal temperature variation would have very little effect on the storage temperature of grain from observations made at different depths within wheat stored in 1000 bushel round metal bins.

Grain is a poor conductor of heat. Heat will be conducted from one grain particle to another only where they touch, and will be radiated across the intergranular air. There may also be mass movement of this intergranular air, transferring heat more quickly by convection. This occurs when there are temperature gradients in the grain, that is, differences in temperature between one part of the grain bulk and another. The thermal conductivity of various grains has been determined by a number of workers[4,6,14,26,33], whose

results are in general agreement. The values given below for wheat in Table 1 were determined at the Pest Infestation Laboratory, England, by Oxley[33].

Table I: Thermal Conductivity of Wheat[33]

Material	Moisture Content	Thermal Conductivity (CGS. Units).
English Wheat	17.8	0.00039
Manitoba Wheat	11.7	0.00036

When grain is stored in bulk, the great thickness involved and the low thermal conductivity will effectively reduce the uptake or loss of heat at the centre of the grain bulk. Williamson[40] has reported that, after harvest in England, cooling of wheat and barley (moisture contents 12.10% - 17.60%) at the average rate of about 1°F in four days appeared to be normal on the vertical axis of unventilated storage bins depending on their capacity and situation. The rate for larger bulks stored on the floor of a general purpose building was somewhat slower, about 1°F per week. The depths ranged from 8 ft. to 20 ft.

Anderson, et al[1], have discussed the effect of temperature differentials on the movement of moisture in stored grain. They carried out a laboratory experiment which suggested that the chief cause of local increases in moisture content of dry wheat stored in country elevator annexes in Western Canada is a temperature differential established during winter. The air in the warmer parts of the grain contained a greater quantity of water vapour than that in the colder, and moisture was transferred either by diffusion or by convective movement. A temperature difference of 95°F., across 6 ft. of grain having an initial moisture content of 14.62%, caused the moisture content at the cold end (32°F) to rise to over 20% in 316 days. The experiment indicated that this movement of moisture is a slow process and that equilibrium conditions are never established for any practical length of time.

In chilled or refrigerated damp grain storage, the chilled air rises in temperature in its passage through the grain and will pick up moisture by evaporation thus providing cooling. Chilling of the grain is thus accomplished by sensible and latent heat removal. Munday[32] records that the quantity of moisture removed is just over 0.35% in barley of 20% moisture content when air-cooled from 70°F to 55°F.

Heating of Stored Grain

The term "spontaneous heating" has long been used to denote the increase in temperature, frequently observed in stored grain or hay, which may occur without any external cause[41]. The heating is a direct result of the respiratory activity of the various biological agencies which are operative in such materials. It usually commences in localised areas of high moisture content and leads to the development of hot spots.

Grain has a low specific heat, and if heat is produced more rapidly than it is dissipated by thermal conduction through the grain, by radiation, by conduction and convection in the intergranular air, and by evaporation of water, the temperature of the grain rises. This rise in temperature increases the rate of respiration so that a continually self-accelerating process takes place. Zeleny[41] has stated that damage from bin heating will occur if the temperature of the grain is allowed to become higher than about 109°F.

Grain stored at moisture contents below those in equilibrium with an intergranular atmosphere of about 75 per cent relative humidity is not subjected to heating over normal storage periods, unless it is infested with insects. The respiratory activity of dry insect-free grain is so low that the small amount of heat produced is normally dissipated without a significant increase in temperature. However, when the moisture content of the grain is sufficiently high to permit fungal growth, the respiratory activity and heat production may be so great that increases in temperature

occur. In bulk grain, fungi and insects are the principal causes of spontaneous heating.

When damp grain is stored in bulk, heating may take place which would not occur in a small sample of the same lot of grain. According to Zeleny[41] this is a result of the so-called "mass effect". As grain is a relatively poor heat conductor and since the loss of heat is proportional to the surface area, the loss is reduced when the mass is increased.

The heating of various agricultural commodities has been a subject of research for many years. One of the earliest controlled studies of heating due to biological agencies was that of Cohn (cited by Milner[30]) in 1890. He showed that moist germinating barley, maintained in an insulated box, could reach a temperature of 104°F at which temperature the germinating barley was killed. This was followed by a secondary rise in temperature to 149°F, which he attributed to thermophilic organisms, principally *Aspergillus fumigatus*. Heating ceased when oxygen was excluded.

Darsie, et al[13], carried out similar studies and pointed out that temperature increases due to the respiration of germinating seeds were slight compared to those caused by fungi. Gilman and Barron[18] confirmed these observations and concluded that these facts strongly suggest the probability that, in bins of stored grain, marked increases in temperature may be ascribed to fungal growth.

Experiments on the rate of respiration, measured by the rate of carbon dioxide production at various moisture contents, have been

occur. In high grain, fungi and insects are the principal causes [illegible]

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carried out at the Pest Infestation Laboratory, England[23], on English wheat. In grain that had been sprayed during development in the ear with a fungistatic substance, and which was free from fungi, the rate of respiration increased relatively little with increasing moisture content. In untreated grain, on the other hand, the rate of respiration rose sharply at moisture contents above 16 percent and this increase was associated with the growth of fungi. In damp grain, therefore, it is the fungi that are primarily responsible for production of heat and not the grain itself.

In the commercial storage of wheat in bulk, heating usually begins in localised areas where conditions are most favourable for fungal growth. Zeleny[41] has reported that, after heating has progressed for a time, the grain gradually cools off and hot spots develop in other parts of the grain bulk. The translocation of moisture from the hot to cool areas appears to be a very probable explanation for this phenomenon. Heating due to fungal growth of course will not proceed beyond about 131°F. Milner,et al[29], have concluded from laboratory experiments that non-biological oxidation proceeds only with difficulty beyond this temperature. The thermal inactivation of the fungi would therefore result in the cessation of heating in such an area and in the slow cooling of the grain due to the dissipation of the heat. Heating above 131°F may be attributed to bacterial and biochemical activity. High temperatures in grain, if they result from spontaneous heating,

are a positive indication of spoilage, and even a slight rise in temperature above what is considered normal under prevailing conditions may indicate an early stage of spoilage.

Semeniuk ,et al[34] ,used fungal development as an indication of the extent of spoilage of grain. The factor most indicative of the condition of grain is kernel damage caused by fungal growth or excessive heating. Fungi of the mold type are the principal micro-organisms affecting grain in storage. Since moisture is necessary for fungal growth, they are the most common cause of initial deterioration of damp grain in farm storage. Their activity lowers the viability, storage qualities, nutritive value and industrial usefulness of grain. Sinha and Wallace[35] have reported that the percentage of grain seeds infested by _Penicillium sp_ increased as the seed germinability decreased.

Moisture

Moisture plays an important role in the safe storage of grain. If the moisture content is maintained at a sufficiently low level, grain can be stored for many years with little deterioration. Low moisture levels limit the development of harmful organisms, namely fungi, bacteria, mites and insects that attack stored grain. The maximum moisture contents for safe storage of some types of wheat in farm-type bins for a period of one year are given in Table 2.

Table 2: Maximum Moisture Contents for Safe Storage[7]

Grain	Moisture Content Percentage (Wet Basis)
Wheat (Hard red winter)	13.0 - 13.5
Wheat (Soft red winter)	13.5 - 14.0
Wheat (Hard red spring)	14.0 - 14.5

Grain will absorb or give up moisture until it is in equilibrium with the surrounding air. The moisture content of the grain when it is in equilibrium with the surrounding atmosphere is called the *Equilibrium Moisture Content* or *Hygroscopic Equilibrium*[19]. The relative humidity of the surrounding atmosphere is known as the *Equilibrium Relative Humidity*[19]. The relative humidity in the intergranular air space in stored grain tends to remain in equilibrium with the moisture in the grain.

The equilibrium moisture content is slightly different according to whether the grain is absorbing or giving up moisture. As shown in Figure I, there is a hysteris effect with the desorption isotherm displaced to the left of the adsorption isotherm[4]. There is also a slight difference in the equilibrium at different temperatures. A rise in temperature lowers the moisture content at a given humidity. Hyde[23] has shown that the equilibrium moisture content is lowered by about 0.6% for each 18°F rise in temperature (Figure 2).

The phenomenon of redistribution of moisture in bins called

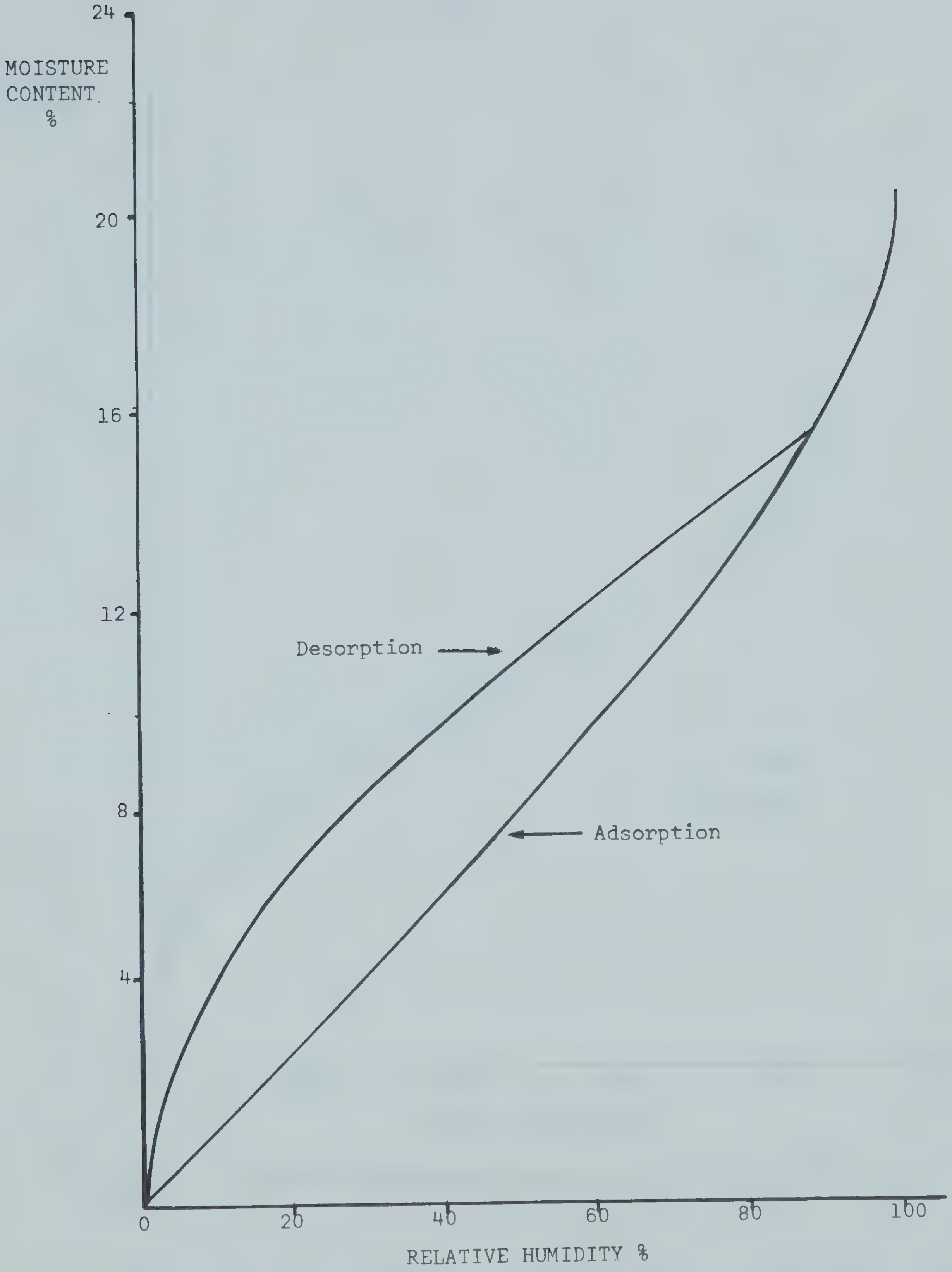


Figure I: Sorption Isotherms For Wheat At 77°F[4].

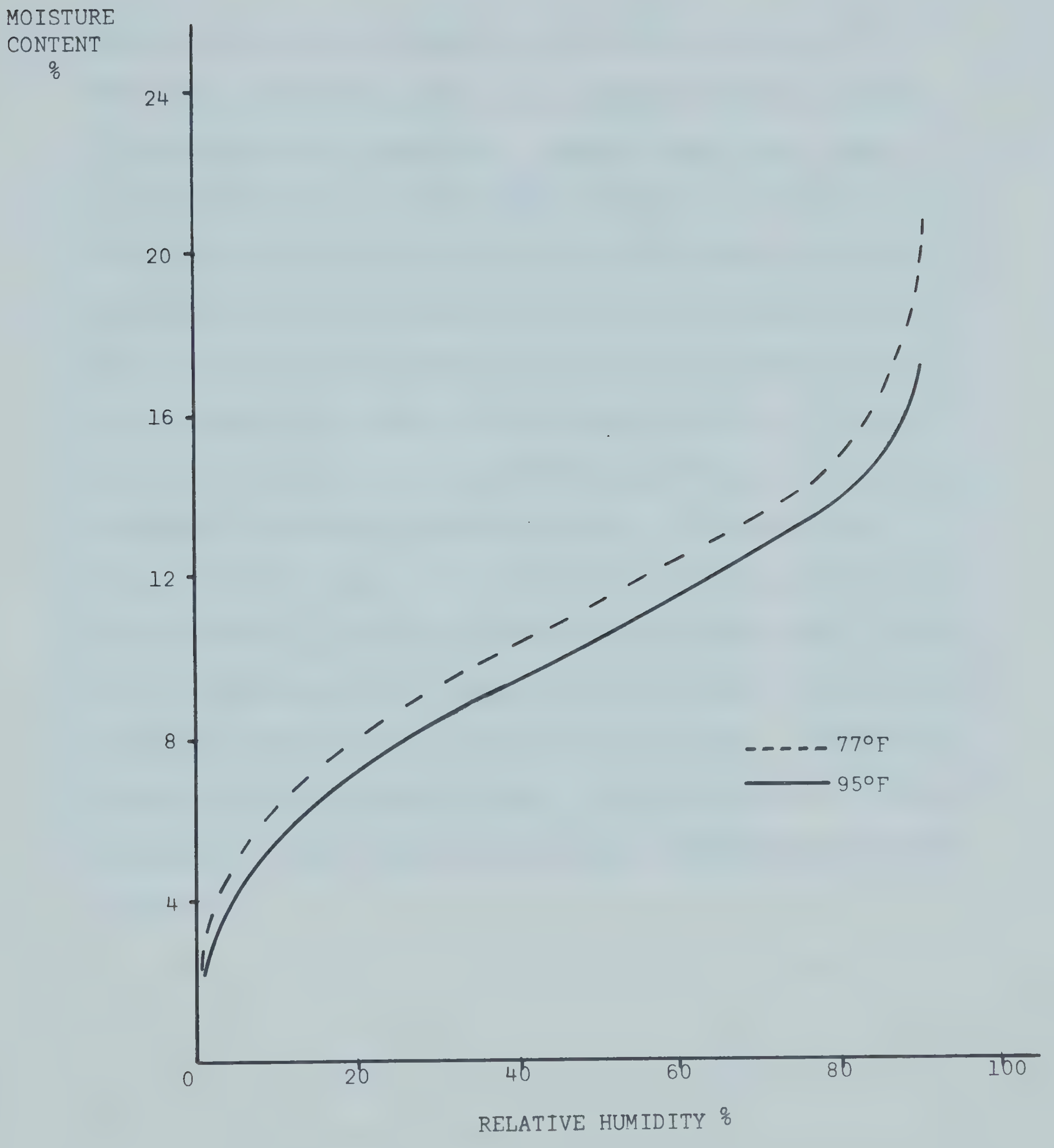


Figure 2: Desorption Isotherms For Wheat At 77°F and 95°F[23].

moisture migration has been observed by Carter and Farrar[11]. The air in the storage space is in constant motion as a result of diffusion and/or convection. When air from a warm region in the grain reaches a cooler region, it must give up some of its moisture to the grain if the equilibrium condition is to be maintained. This interchange of moisture usually takes place entirely in the vapour phase, but, in extreme instances, warm air reaching a cold region in the storage space may be cooled below its dew point, with condensation occuring on the cold surfaces of the grain or walls of the bin. Thus moisture is transported from warmer to cooler regions of the stored grain and spoilage as a result of excessive moisture may occur in parts of the storage space even though none of the grain initially contained sufficient moisture to promote spoilage. This problem becomes critical in large storages. Storages containing less than 3000 bushels do not experience significant trouble with moisture migration[3].

PRELIMINARY STUDY

A preliminary study was carried out in 1967 by the Department of Agricultural Engineering, University of Alberta, on the heating and spoilage of damp grain in storage. The study was to yield information on the effect of temperature on the keeping quality of tough and damp grain, where keeping quality may be defined as those characteristics of the grain which enable it to resist attack by spoilage organisms.

For the project, a wooden bin, 7' 6" x 8' x 8' high (Figure 3), was filled with 300 bushels of No. 1 grade Thatcher wheat. Ten thermocouples, connected to a 12-point millivolt recorder having an ice-bath as a reference junction, were stationed at different points in the wheat to measure grain temperatures. Ambient air, humidified by passing through a spray washer via floor ducts as a means of increasing the moisture content of the dry wheat, was blown through the grain. For the purposes of sampling, the bin was arbitrarily divided into three layers, namely top, middle and bottom. Grain samples were taken from these layers, with a probe sampler, for moisture and microbial analyses. Moisture contents were determined by a Halcross Moisture Meter and microbial analysis by culturing fungi on Czapeck's agar medium in petri-dishes.

At the start of the study, the wheat grain had a uniform moisture content of 11.40%. Following the passage of the humidified air through the grain, sampling revealed that the distribution of moisture content in the bin was not uniform. Since the moist air was

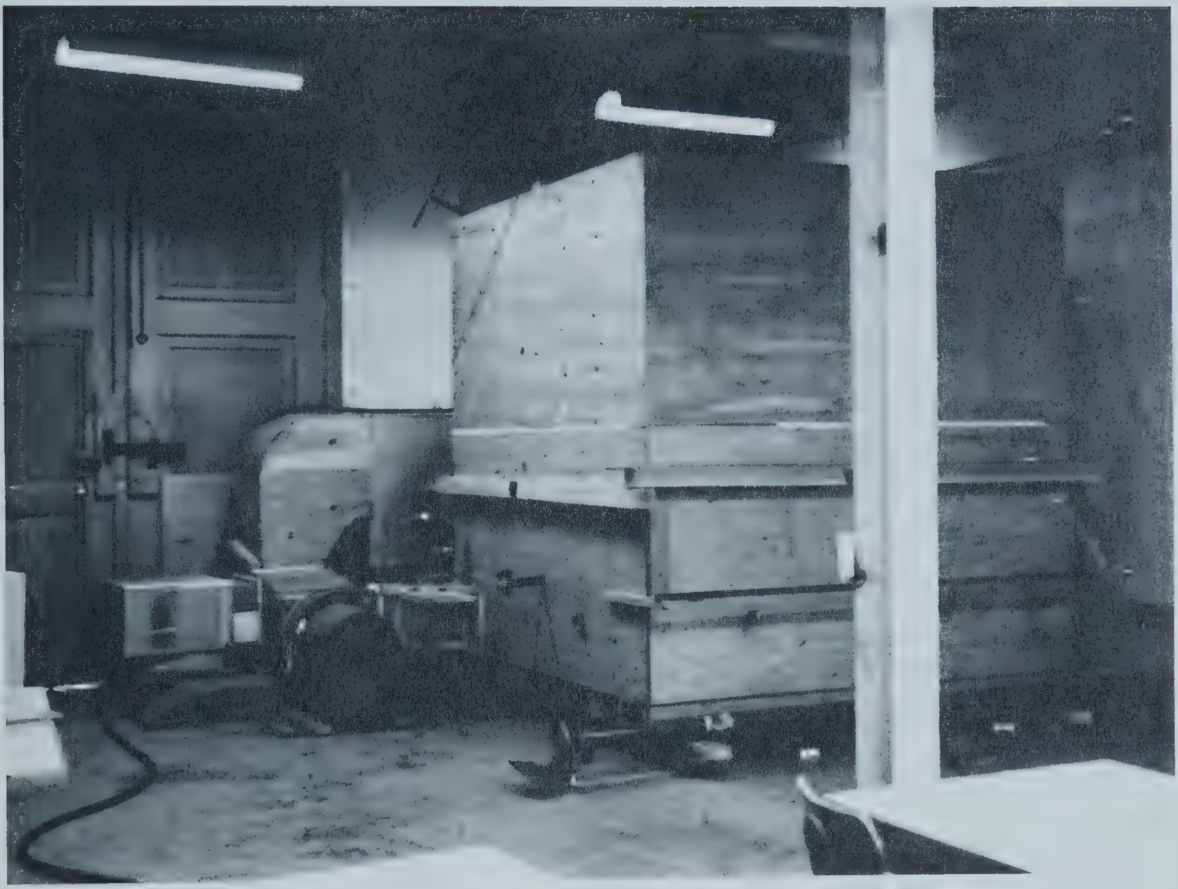


Figure 3: Storage Bin Facilities Used In Preliminary Study.

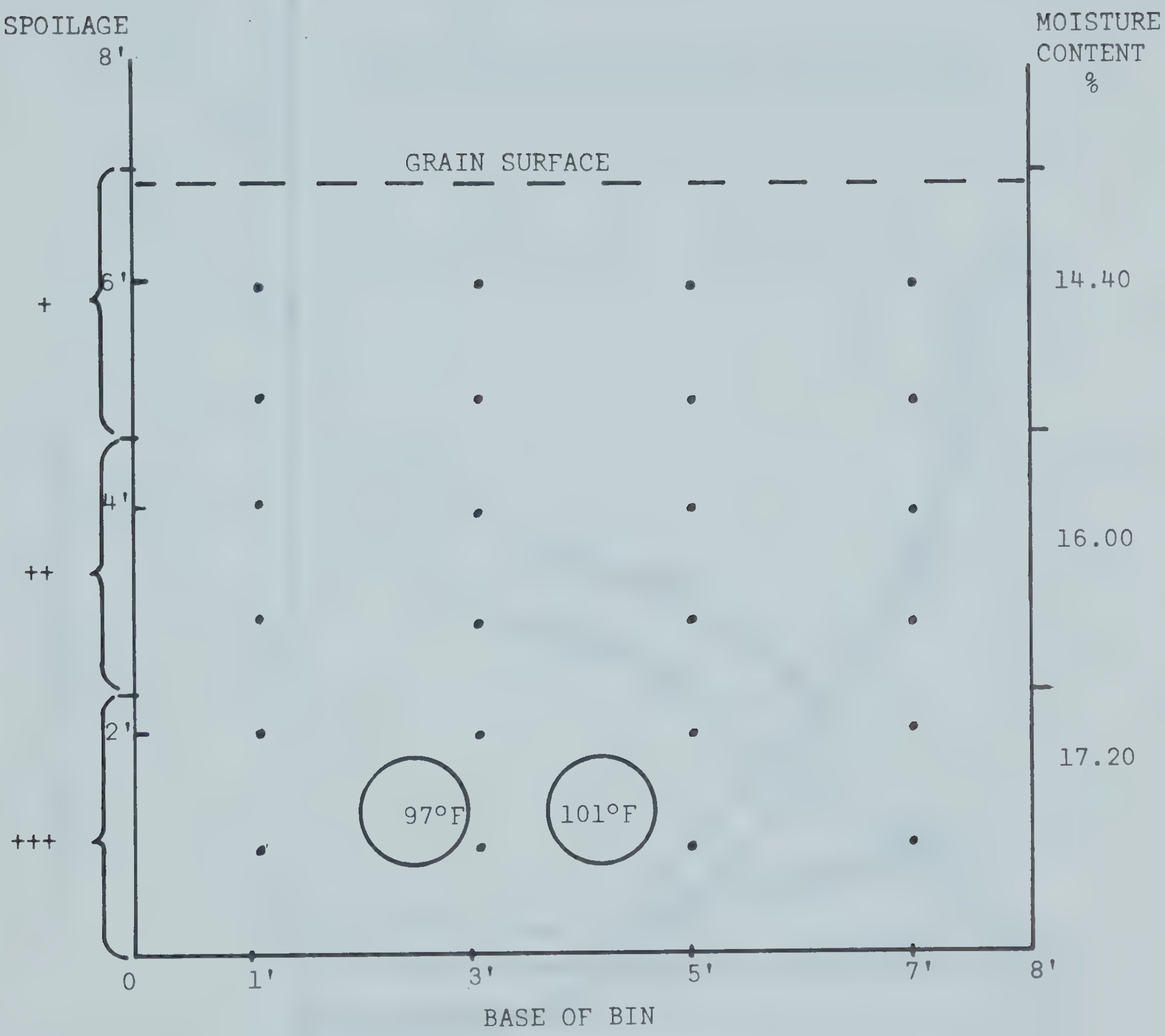
introduced at the bottom of the bin, it was to be expected that a moisture gradient in the grain would be established, with the moisture content highest at the bottom and lowest at the top. Thus layers of dry, tough and damp wheat were established in the bin with average moisture contents of 14.40%, 16.00% and 17.20% respectively (Figure 4).

The grains were healthy at the beginning of the project with samples showing a germination range of 95-98%. The following fungi were recorded initially from microbial analyses (Table 3).

Table 3: Microbial Analysis

Fungus	Frequency (% Wheat infested)
1. Alternaria sp	65%
2. Fusarium sp	58%
3. Absidia sp	10%
4. Rhizopus sp	15%
5. Aspergilli & Penicilli sp	3%

Analyses were continued at 3 months intervals and the average percentage of various fungi infesting the wheat grain were recorded. The results of these analyses are represented graphically in Figure 5. With increase in storage time and rise in moisture content commencing at the 6th month, the species of Alternaria and Fusarium started declining. By the time the final observation was made, that



+++: Maximum Spoilage
++: Moderately Spoiled
+: Slightly Spoiled

Figure 4: Diagram Showing Sampling Points,Moisture Content And Spoilage. (Preliminary Study)

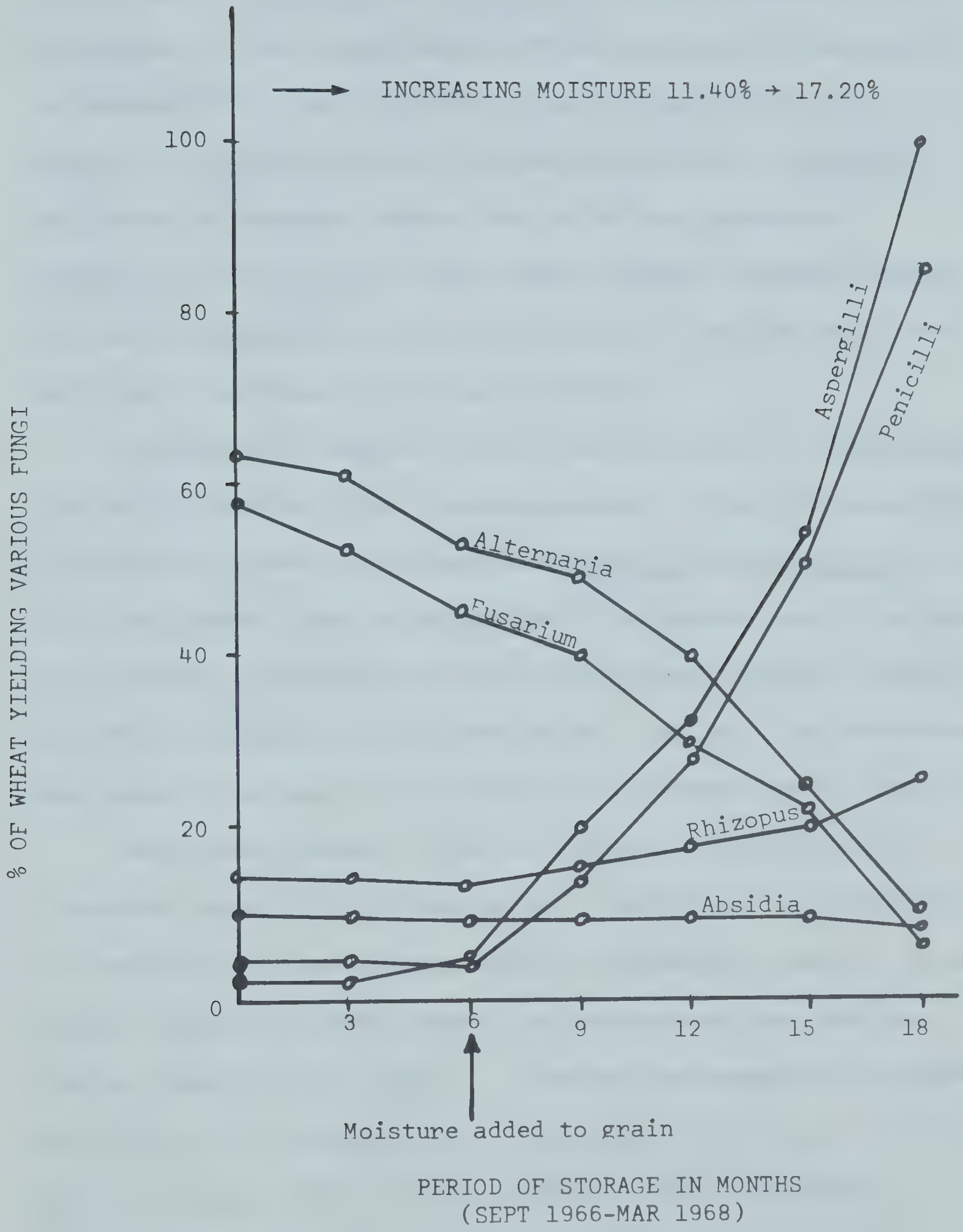


Figure 5: Fungal Growth Curves (Preliminary Study)

is, after 18 months storage only 9 to 10% of the grains showed these fungi. Alternaria and Fusarium are "field fungi" and are considered not to be associated with the spoilage of wheat grain in storage[12,35]. The incidence of the two saprophytic fungi, Absidia and Rhizopus did not show much alteration. Rhizopus sp registered an increase towards the end of the experiment. Aspergilli and Penicilli, both showed a gradual increase from the 6th month storage point, this coinciding with the date when the addition of moisture to the grain commenced.

As pointed out earlier, the bottom portion of the bin contained the grain with the highest moisture content. From this area, 100% of the grain showed the presence of Aspergilli and Penicilli. The grain was almost black in appearance. The germination of the grain was severely affected by the time of the final analysis. Only 10 to 15% of the grains showed germination. The grain was moderately and slightly spoiled at the middle and top respectively (Figure 4).

Temperature changes in the bin during the storage period proceeded slowly in the three layers. Spectacular hot spots were not recorded, but two thermocouples in the bottom, that is, in the area of highest moisture content and maximum spoilage gave the highest temperatures (Figure 4). The maximum temperature recorded was 101°F at the central part of the bottom of the bin. The wheat grains at the bottom of the bin showed a burned appearance.

The average room temperature during the period of the experiment was about 70°F.

This preliminary study showed that:

(a) maximum fungal spoilage occurred in the area of highest moisture content,

(b) temperature rise in the bin proceeded slowly, with "hot spots" occurring in the area of highest moisture content and maximum spoilage, and

(c) heating produced a burned appearance of the grain.

With the exception of slow temperature rise, the findings are in general agreement with published work in this area.

In this preliminary study, no attempt was made to investigate wheat storage as it would occur in practice on the farm. In any further investigation, it was felt that the influence of the winter and spring temperature cycle on the stored grain should be included in the study. This was undertaken and the cycle was simulated in the major project.

EXPERIMENTAL PROCEDURE

Materials

Environmental Chamber and Warm Enclosure

An environmental chamber, normally used for cold temperature animal physiology studies, and a warm enclosure were used for the experiment. The dimensions of the cold chamber were 9 ft. by 10 ft. by 7 ft. to a false ceiling. The space above this ceiling housed two refrigeration units and acted as a plenum to ensure uniform distribution of the cold air. The chamber was designed to provide temperatures down to -30°F under summer conditions. Any desired temperature down to this figure could be achieved by an appropriate adjustment of a thermostat. Since the suspended floor of the chamber was not designed to carry the loading imposed by the grain involved in the project, it was necessary to strengthen it. This was readily taken care of by supporting the existing floor with 6" x 6" beams carried on Hallrein telescoping posts from the basement below. The door of the chamber, of coldstore type, was 6 1/2 ft. high and 6 ft wide.

The warm enclosure was a building section 14 ft. by 10 ft. by 10 ft. high maintained at a room temperature of 70°F. The temperature was controlled by means of a thermostat.

A maximum and minimum thermometer with a temperature range from -50°F to 130°F was used to record variations in the temperature of the environment.

Metal Bins

Four circular bins of 18 gauge galvanised steel were used in the experiment. Each bin was 4 ft. in diameter and 5 ft. high. The metal bins were set on 4 ft. by 4 ft. base frames with wheels to facilitate movement (Figure 6).

Temperature Instrumentation

Copper-constantan thermocouples were used for temperature measurements. Each bin contained twenty-four thermocouples, suspended on cross-bars fitted across the top (Figure 7) and arranged in two layers, 12 ins. and 36 ins. from the base of the bin. The twelve thermocouples in each layer were arranged on two diameters perpendicular to each other. The six thermocouples on each diameter were 8 inches apart with the two outermost ones 4 ins. from the periphery. Thus, on any radius, the spacings were 4 ins., 12 ins. and 20 ins. from the centre. The thermocouple arrangement in each bin is illustrated in Figures 8 and 9.

Temperature Recorder

Temperatures were recorded on a 24-point Honeywell temperature recorder with a scale range of -25°F to 125°F (Figure 10). The 96 thermocouples from the bins were wired to a switching device consisting of two 24 pole, 4-position switches. These in turn were wired to the recorder to allow 24 temperatures to be recorded at a time. The wiring was such that 24 thermocouples from one bin were controlled by one switch position. Recording was sequential, taking 7 minutes for the range of 24 temperatures.

Figure 6: View Of Bin Amd Recorder.

Figure 7: Top View Of Bin Showing Cross-Bar Support For The Thermocouples.

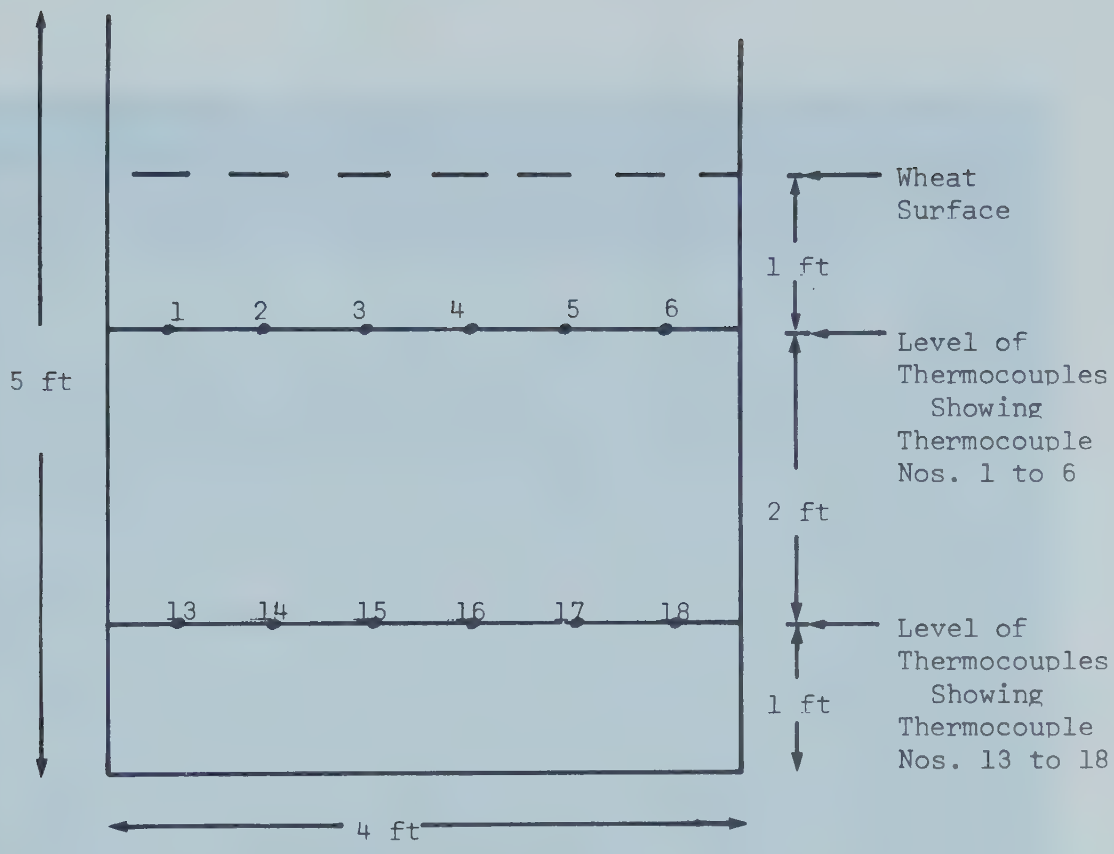


Figure 8: Vertical Section Along Diameter Of Bin.

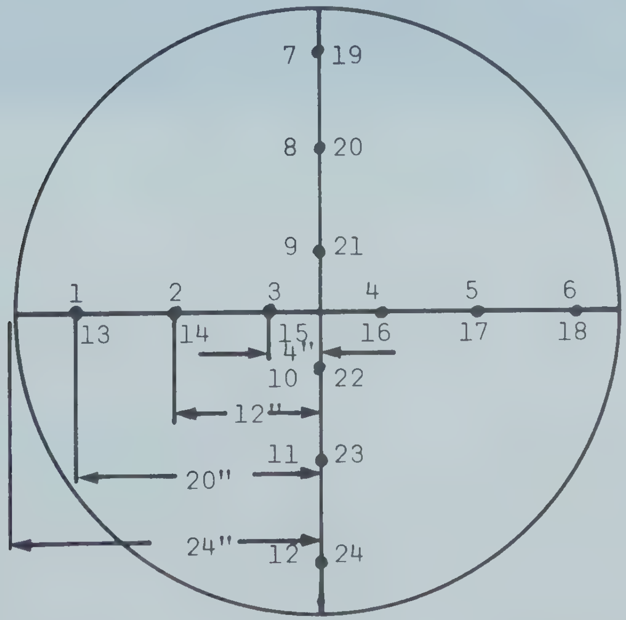


Figure 9: Cross-Section Of Bin Showing Radial Spacing Of Thermocouples.

Thermocouples 1 to 12 are in Upper Layer.
Thermocouples 13 to 24 are in Lower Layer.

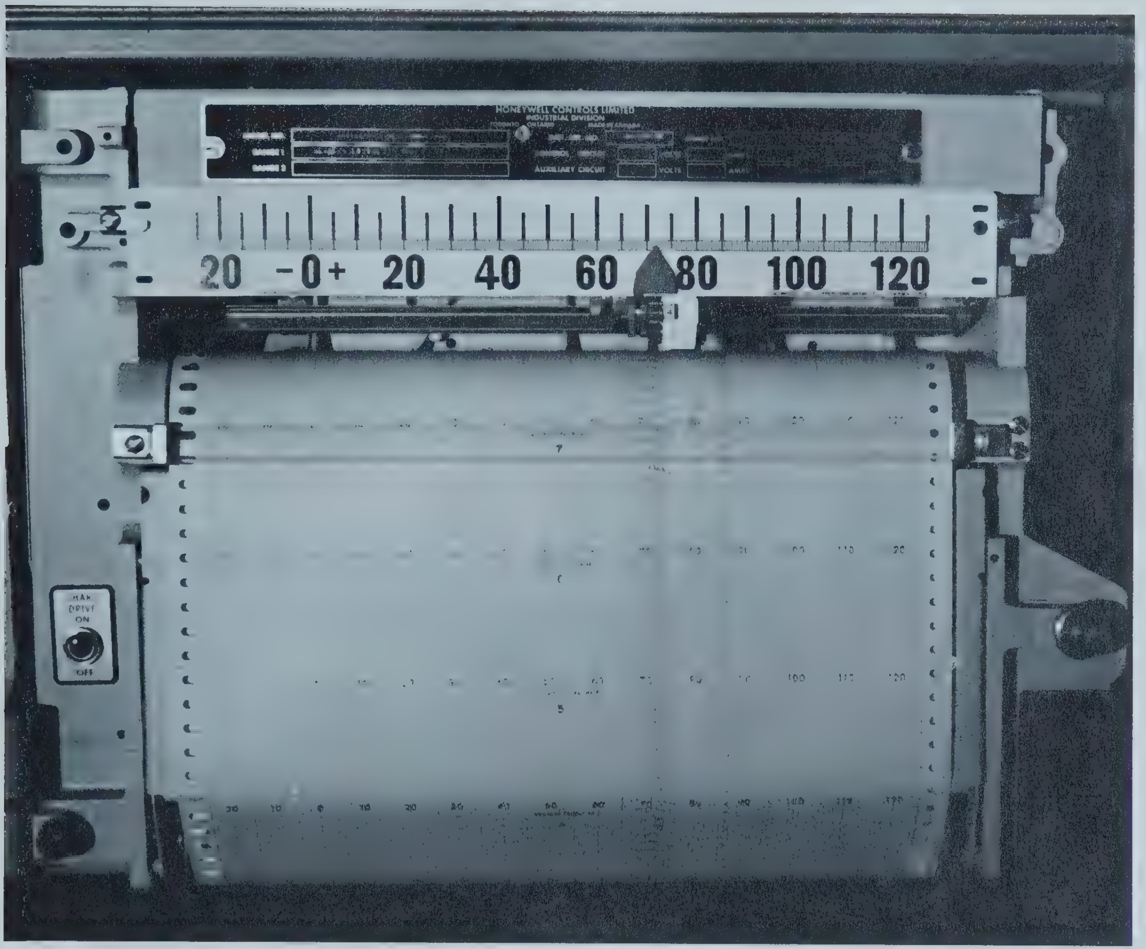


Figure 10: Recorder Chart.

Wheat

The grain used in the experiment was Grade I Manitou seed wheat. The total volume used was 164 bushels.

Moisture Content Instrumentation

Direct and indirect methods are available for determining moisture content of grain. The direct methods are usually accepted as standard for moisture determination[19,21]. The major direct methods are oven, desiccant-drying and distillation. The air-oven was used for moisture content determinations of samples taken during the experiment.

Methods

Increasing the Wheat Moisture Content

Hustrulid[22] has reported that the characteristics of naturally moist and remoistened wheat are not significantly different. The preliminary study indicated that, with humidified air, the moisture content of the wheat increased slowly. Thus the alternative method of direct water application to the grain was used to increase the moisture content.

The wheat as delivered by the supplier was found to have a moisture content of 11.35% (wet basis). For the purposes of the study, it was necessary to raise this moisture content for half of the 164 bushels, to a level of 16-17%. The water was added by means of a sprinkler to the grain which was turned continuously in a tractor-powered auger cart as shown in Figure 11.

Figure 11: Tractor, Auger Cart And Sprinkler Used In Increasing Grain Moisture Content.

Loading of Bins

Each bin was loaded with 41 bushels of wheat to a height of 4 ft. The bins were identified by the numbers 1,2,3, and 4. Bins 1 and 4 contained dry grain with an average moisture content of 11.35% (wet basis) and bins 2 and 3 tough grain with an average moisture content of 16.46% (wet basis). The thermocouples were placed carefully in position in the grain by hand as filling proceeded.

Cooling and Warming

The bins were set first in the cold chamber and later in the warm enclosure as shown in Figures 12 and 13 respectively. They were arranged as shown in Figures 14 and 15. The temperature of the cold chamber was reduced from about 70°F to -20°F progressively over four days. The -20°F temperature was maintained for a further 24 consecutive days. The environmental temperature fluctuated only slightly over a 24 hour period from -19°F to -21°F as recorded by the maximum and minimum thermometer.

After 28 days cooling, the warming process was introduced. The temperature in the cold chamber was increased progressively over four days to avoid condensation in the grain. The bins were transferred to the warm enclosure on the 4th day. The grain warmed up under the influence of the room temperature for a further 31 consecutive days. At the end of 35 days of warming, temperature recording ceased and sampling began. The temperature in the warm enclosure gave a maximum fluctuation of 10°F (60°F - 70°F) over

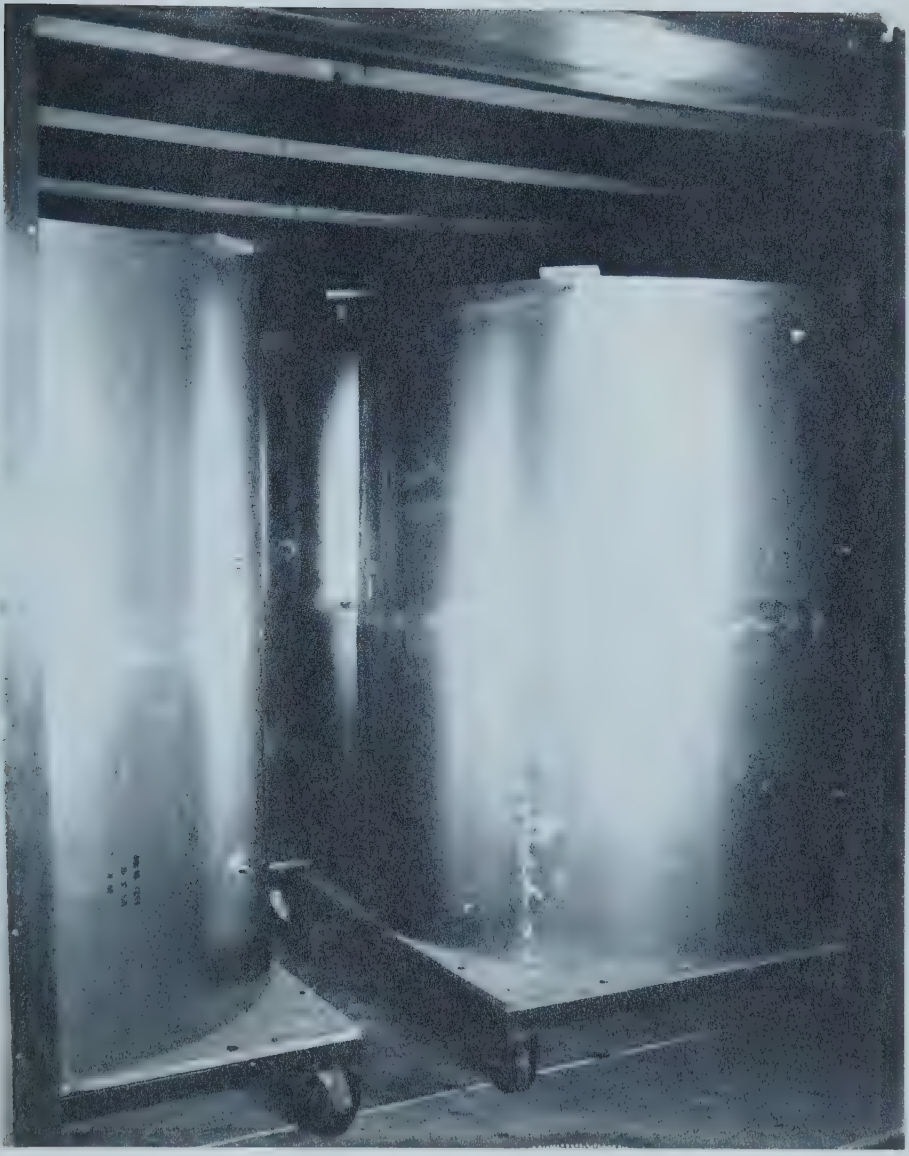


Figure 12: Bins Positioned In The Cold Chamber.

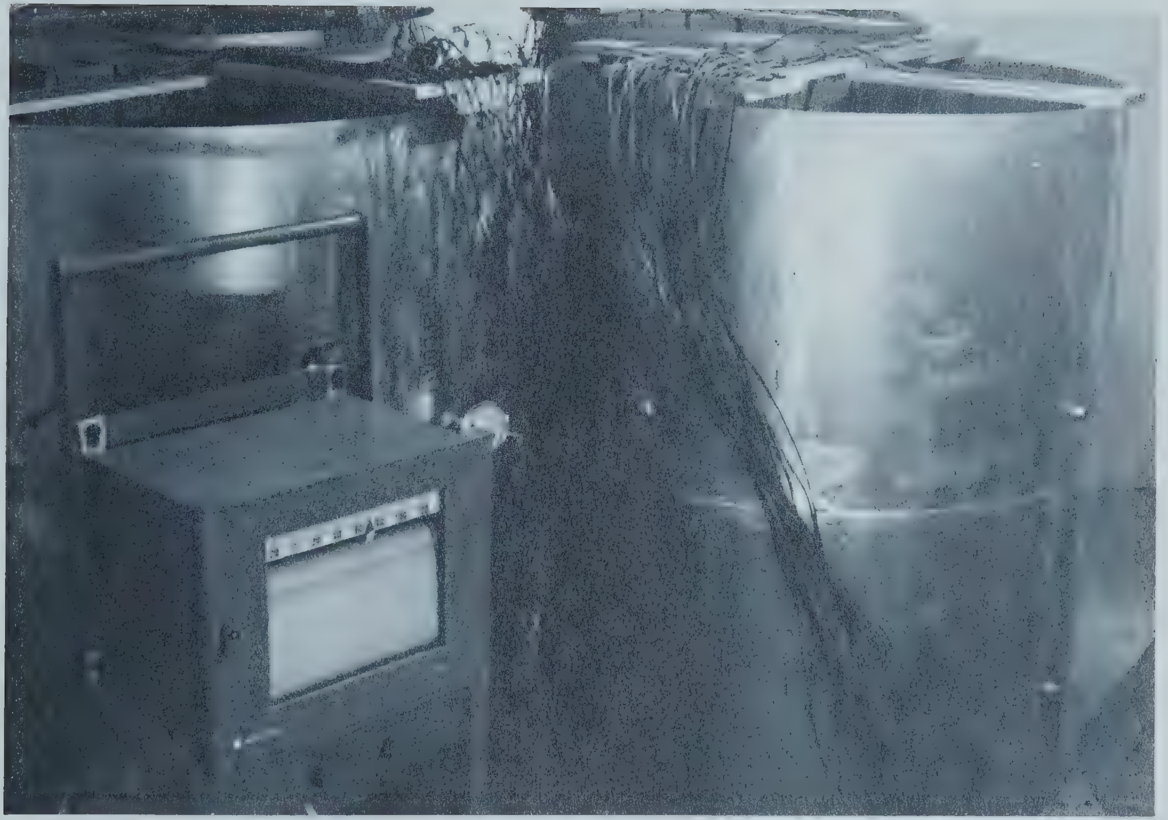


Figure 13: Bins And Recorder In The Warm Enclosure.

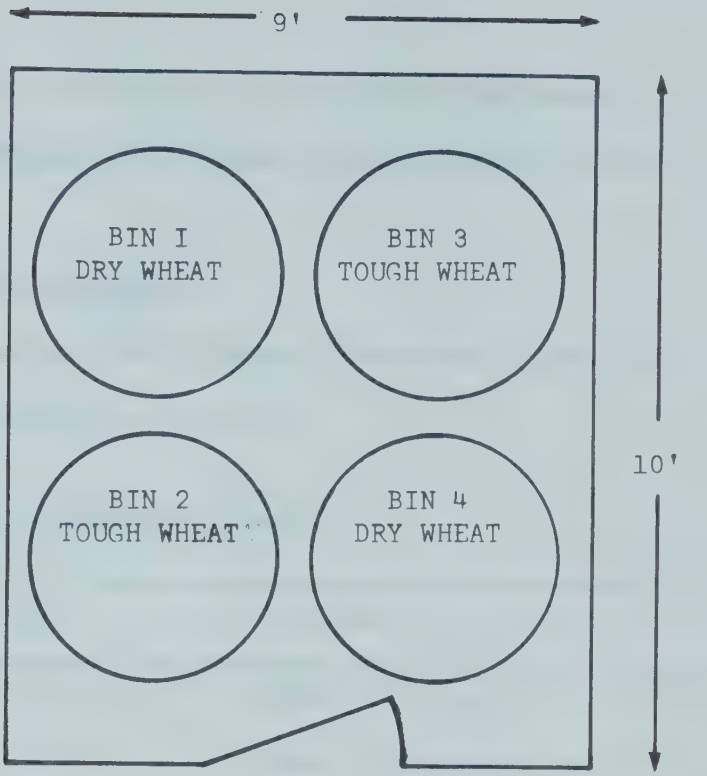


Figure 14: Arrangement of Bins In The Cold Chamber.

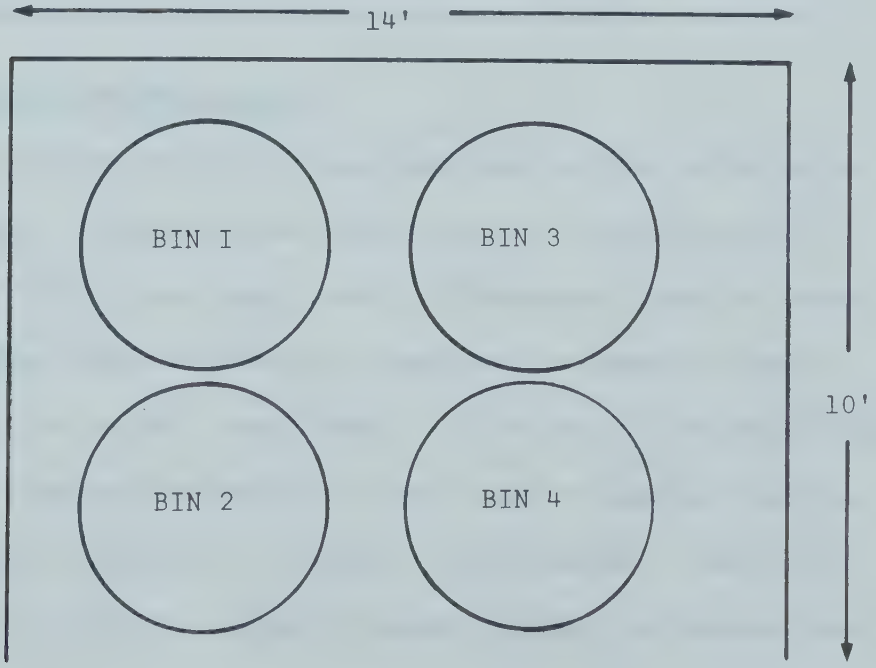


Figure 15: Arrangement Of Bins In The Warm Enclosure.

one 24 hour period. This was due to diurnal temperature fluctuations. Generally the 24 hour period fluctuation was much less.

Temperature Recording Schedule

The temperatures at the different thermocouple positions in each bin were recorded as follows:

Table 4: Temperature Recording Schedule.

Bin	Time
1	8 a.m. - 10 a.m.
2	10 a.m. - 12 noon
3	12 noon - 2 p.m.
4	2 p.m. - 4 p.m.

Moisture Content Determinations

Air-oven method determinations were made at the beginning of the experiment. Determinations were made on 40 random samples from the bulk of dry and tough wheat, 20 from each class of wheat. By using random number tables, the samples were taken at random from the bags of dry and tough wheat. At the end of the experiment, the moisture content determinations were made on samples from the 96 thermocouple positions. To collect these samples, the grain was removed in layers by vacuum to ensure minimum disturbance and mixing in the bin. At the level of the thermocouples, the kernels in the neighbourhood of the thermocouples were removed carefully

by hand with a metal scoop. Samples collected weighed about 120 gms each. The weight of each sample used in the air-oven test was 100 grams. This was placed in the oven for 24 hours at 266°F. The loss in weight was recorded as the percentage in moisture content (wet basis).

Microbial Analysis

For this analysis, 7 grams of the samples collected for moisture content determination were used. From each sample of 7 grams, 100 kernels were placed on 4 petri-dishes containing Czapeck's agar medium. 25 kernels were spaced as evenly as possible on each petri-dish. The petri-dishes were left at room temperature for 4 to 6 days. The grains were then examined for the growth of fungi. The number of wheat grains yielding various fungi were recorded.

DATA ANALYSIS AND RESULTS

Grain Temperatures

For the purposes of analyses, the daily cycle of temperatures recorded at 9 a.m. for Bin No. 1 (dry wheat), 11 a.m. for Bin 2 (tough), 1 p.m. for Bin 3 (tough) and 3 p.m. for Bin 4 (dry) was used. These temperatures were combined to give average temperatures for each bin at each of the locations 20 ins., 12 ins., and 4 ins. from the centre of the bin for the two layers, 12 ins. and 36 ins. from the base of the bin. The temperatures recorded are given in Appendix I. The averages were punched on cards to be used in programs written for the IBM 360 model 67 computer.

The physical factors influencing the grain temperature in this experiment were environmental temperature, moisture content of the grain, time, height from the bin base and the radial distance from the bin centre. In either the cooling or the warming process, the environmental temperature was considered to be constant. Within each bin, the moisture content was also considered to be constant.

Statistical Analyses

To determine whether the various factors and their interactions differred between each other, an analysis of variance was used. Also a prediction of grain temperatures using one or more of the measured variables was made using multiple linear regression. Calculations of both the analysis of variance and the multiple linear regression were made using programs of the University of Alberta Computing Centre[15,16,24].

Analysis of Variance

The model for the analysis of variance was:

$$\begin{aligned} Y_{ijkmn} = {} & u + D_i + S_j + DS_{ij} + L_k + DL_{ik} + SL_{jk} + DSL_{ijk} \\ & + M_m + DM_{im} + SM_{jm} + DSM_{ijm} + LM_{km} + DLM_{ikm} + SLM_{jkm} \\ & + DSLM_{ijkm} + D/M_{n(m)} + DB/M_{in(m)} + SB/M_{jn(m)} + DSB/M_{ijn(m)} \\ & + LB/M_{kn(m)} + DLB/M_{ikn(m)} + SLB/M_{jkn(m)} + DSLB/M_{ijkn(m)} \end{aligned}$$

where Y_{ijknm} is the measurement of the n^{th} bin of the m^{th} moisture of the k^{th} layer of the j^{th} spacing of the i^{th} day.

$i = 1, 2, \ldots\ldots\ldots\ldots, 28$

$j = 1,2,3$

$k = 1, 2$

$m = 1,2$

$n = 1, 2$

All factors except bins were considered as fixed.

The correct terms for test of significance were determined using a procedure based upon the rules for obtaining the Expected Mean Squares outlined by Bennett and Franklin[17], and are given in Table 5.

The proper F test for each mean square can be determined by using the E.M.S. The significance of the variance of a factor is determined by comparing the mean square that includes the variance estimate of the factor with the mean square that includes the same variance estimates as the first mean square excepting the factor under test[38].

Table 5: Table of Expected Mean Squares (E.M.S.)

SOURCE OF VARIATION	DEGREES OF FREEDOM	E.M.S.
D_i = Day	27	$\sigma_e^2 + 6\sigma^2_{DB} + 24\sigma^2_D$
S_j = Spacing	2	$\sigma_e^2 + 56\sigma^2_{SB} + 224\sigma^2_S$
DS_{ij}	54	$\sigma_e^2 + 2\sigma^2_{DSB} + 8\sigma^2_{DS}$
L_k = Layer	1	$\sigma_e^2 + 84\sigma^2_{LB} + 336\sigma^2_L$
DL_{ik}	27	$\sigma_e^2 + 3\sigma^2_{DLB} + 12\sigma^2_{DL}$
SL_{jk}	2	$\sigma_e^2 + 28\sigma^2_{SLB} + 112\sigma^2_{SL}$
DSL_{ijk}	54	$\sigma_e^2 + \sigma^2_{DSLB} + 4\sigma^2_{DSL}$
M_m = Moisture	1	$\sigma_e^2 + 168\sigma^2_B + 336\sigma^2_M$
DM_{im}	27	$\sigma_e^2 + 6\sigma^2_{DB} + 12\sigma^2_{DM}$
SM_{jm}	2	$\sigma_e^2 + 56\sigma^2_{SB} + 112\sigma^2_{SM}$
DSM_{ijm}	54	$\sigma_e^2 + 2\sigma^2_{DSB} + 4\sigma^2_{DSM}$
LM_{km}	1	$\sigma_e^2 + 84\sigma^2_{LB} + 168\sigma^2_{LM}$
DLM_{ikm}	27	$\sigma_e^2 + 3\sigma^2_{DLB} + 6\sigma^2_{DLM}$
SLM_{jkm}	2	$\sigma_e^2 + 28\sigma^2_{SLB} + 56\sigma^2_{SLM}$
$DSLM_{ijkm}$	54	$\sigma_e^2 + \sigma^2_{DSLB} + 2\sigma^2_{DSLM}$
$B/M_{n(m)}$ (B = Bin)	2	$\sigma_e^2 + 168\sigma^2_B$
$DB/M_{in(m)}$	54	$\sigma_e^2 + 6\sigma^2_{DB}$
$SB/M_{jn(m)}$	4	$\sigma_e^2 + 56\sigma^2_{SB}$
$DSB/M_{ijn(m)}$	108	$\sigma_e^2 + 2\sigma^2_{DSB}$
$LB/M_{kn(m)}$	2	$\sigma_e^2 + 84\sigma^2_{LB}$
$DLB/M_{ikn(m)}$	54	$\sigma_e^2 + 3\sigma^2_{DLB}$
$SLB/M_{jkn(m)}$	4	$\sigma_e^2 + 28\sigma^2_{SLB}$
$DSLB/M_{ijkn(m)}$	108	$\sigma_e^2 + \sigma^2_{DSLB}$
TOTAL	671	

Results of the Analysis of Variance

The temperature means for days, radial spacing, layer and moisture are given in Table 6 for cooling and in Table 7 for warming. The analysis of variance are given in Table 8 for cooling and Table 9 for warming.

Significant differences existed for all main effects. The main effects due to Day and Spacing were highly significant during cooling and the main effects due to Day, Spacing and Layer (height) were highly significant during warming. The significance of the main effects indicated that the variation of temperatures from day to day over the 28 day period, among the three radial spacings, between the two layers, and between the dry and tough wheat were statistically significant.

Although for the factors considered, there are first-, second- and third- order interactions in this experiment, only the first order interactions were regarded as being of practical interest. The first order interactions Day x Spacing, Day x Layer, Day x Moisture were highly significant during cooling. Layer x Moisture was significant but not highly significant during cooling. Day x Spacing, Day x Layer, Spacing x Layer and Day x Moisture were all highly significant during warming. The interaction of day and spacing (DS), day and layer (DL) and of day and moisture (DM) may be observed in Figures 16 and 17, Figures 18 and 19 and Figures 20 and 21 respectively where the grain temperature is plotted against days for each of the three radial positions (Figures 16 and 17) for each of the two horizontal layers (Figures 18 and 19) and for the dry and tough wheat (Figures 20 and 21). The significance of these interactions, Day x Spacing, Day x Layer and Day x Moisture, indicated that the differences among the rates of cooling

Table 6: Mean Temperatures In °F For The Factors During Cooling

MEANS OF DAYS

DAY	TEMPERATURE	DAY	TEMPERATURE	DAY	TEMPERATURE
1	70.76	11	2.47	21	-14.99
2	61.87	12	- 0.97	22	-15.66
3	54.43	13	- 3.43	23	-16.33
4	47.66	14	- 5.56	24	-16.63
5	39.08	15	- 7.64	25	-16.81
6	30.66	16	- 9.56	26	-17.29
7	22.87	17	-11.10	27	-17.29
8	16.29	18	-12.24	28	-17.29
9	10.61	19	-13.35		
10	6.06	20	-14.24		

MEANS OF RADIAL SPACING

20 ins.	12 ins.	4 ins.
- 1.14	6.48	10.98

MEANS OF LAYER

Upper	Lower
4.27	6.61

MEANS OF MOISTURE

Low	High
3.40	7.48

GRAND MEAN

5.44

Table 7: Mean Temperatures In °F For The Factors During Warming

MEANS OF DAYS

DAY	TEMPERATURE	DAY	TEMPERATURE	DAY	TEMPERATURE
1	-10.56	11	54.57	21	66.49
2	- 4.17	12	56.69	22	67.15
3	5.64	13	58.58	23	67.74
4	15.75	14	60.56	24	68.47
5	24.31	15	62.12	25	69.02
6	31.82	16	63.39	26	69.95
7	38.22	17	64.13	27	70.48
8	43.17	18	64.67	28	70.83
9	47.62	19	65.31		
10	52.01	20	65.69		

MEANS OF RADIAL SPACING

20 ins.	12 ins.	4 ins.
55.71	49.42	45.89

MEANS OF LAYER

Upper	Lower
54.81	45.87

MEANS OF MOISTURE

Low	High
52.02	48.67

GRAND MEAN

50.34

Table 8: Analysis of Variance (Cooling)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F
Day	27	472280.00	17492.00	9819.00**
Spacing	2	16834.00	8417.00	570.10**
DS	54	11369.00	210.54	274.10**
Layer	1	913.15	913.15	51.89*
DL	27	483.28	17.90	26.51**
SL	2	40.04	20.02	4.73
DSL	54	112.15	2.08	6.25**
Moisture	1	2791.20	2791.20	78.63*
DM	27	778.96	28.85	16.20**
SM	2	186.82	93.41	6.32
DSM	54	93.86	1.74	2.26**
LM	1	343.67	343.67	19.55*
DLM	27	288.37	10.68	1.58
SLM	2	210.78	105.39	24.92**
DSLM	54	155.14	2.87	8.64**
Bin/M	2	70.96	35.48	56.41*
DB/M	54	96.19	1.78	
SB/M	4	59.08	14.77	
DSB/M	108	82.93	0.77	
LB/M	2	35.19	17.60	
DLB/M	54	36.47	0.68	
SLB/M	4	16.92	4.23	
DSLB/M	108	35.91	0.33	
TOTAL	671			

* Significant at .05 probability level[37].

** Significant at .01 probability level.

Table 9: Analysis of Variance (Warming)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F
Day	27	365590.00	13540.00	2563.00**
Spacing	2	11084.00	5542.10	533.50**
DS	54	8912.10	165.04	364.30**
Layer	1	13417.00	13417.00	644.20**
DL	27	6060.90	224.48	380.80**
SL	2	368.55	184.28	18.77**
DSL	54	359.09	6.65	1.77**
Moisture	1	1880.90	1880.90	60.39*
DM	27	1067.70	39.54	7.48**
SM	2	93.67	46.84	4.51
DSM	54	94.12	1.74	3.85**
LM	1	43.13	43.13	2.07
DLM	27	480.61	17.80	30.19**
SLM	2	122.97	61.48	6.26
DSLM	54	201.18	3.73	9.90**
Bin/M	2	62.28	31.14	53.11*
DB/M	54	285.40	5.29	
SB/M	4	41.57	10.39	
DSB/M	108	48.92	0.45	
LB/M	2	41.66	20.83	
DLB/M	54	31.84	0.59	
SLB/M	4	39.27	9.82	
DSLB/M	108	40.66	0.38	
TOTAL	671			

* Significant at .05 probability level.

** Significant at .01 probability level.

and warming at the three radial spacings, between the rates of cooling and warming at the two horizontal levels and between the rates of cooling and warming of the dry and tough wheat were statistically significant.

As found by earlier workers[5,10,40], the grain surface responded more quickly to the external temperature than the inner portion of the grain mass. Wheat at the 20 ins. radial position cooled and warmed significantly faster than the wheat at the 12 ins. and 4 ins. radial positions; and wheat at the 12 ins. radial position cooled and warmed significantly faster than wheat at the 4 ins. radial positions (Figures 16 and 17). Cooling and warming of the wheat were significantly faster at the upper horizontal level than at the lower level (Figures 18 and 19). However during warming the variation in the two levels was considerably greater than that during cooling.

The dry wheat cooled significantly faster than the tough wheat under the influence of the external temperature (Figure 20). The temperatures of both types of grain dropped quickly in the first 21 days of cooling and then slowed down. The temperatures tended to stabilise as the temperature of the environment (-20°F) was approached. The dry grain heated significantly faster than the tough grain based on the 28 days of warming (Figure 21). However, temperatures in the latter had caught up by the 25th day as shown in Figure 21. The tough grain was thus beginning to heat faster than the dry grain after the 25th day. At the time this occurred, temperatures in both dry and tough wheat had

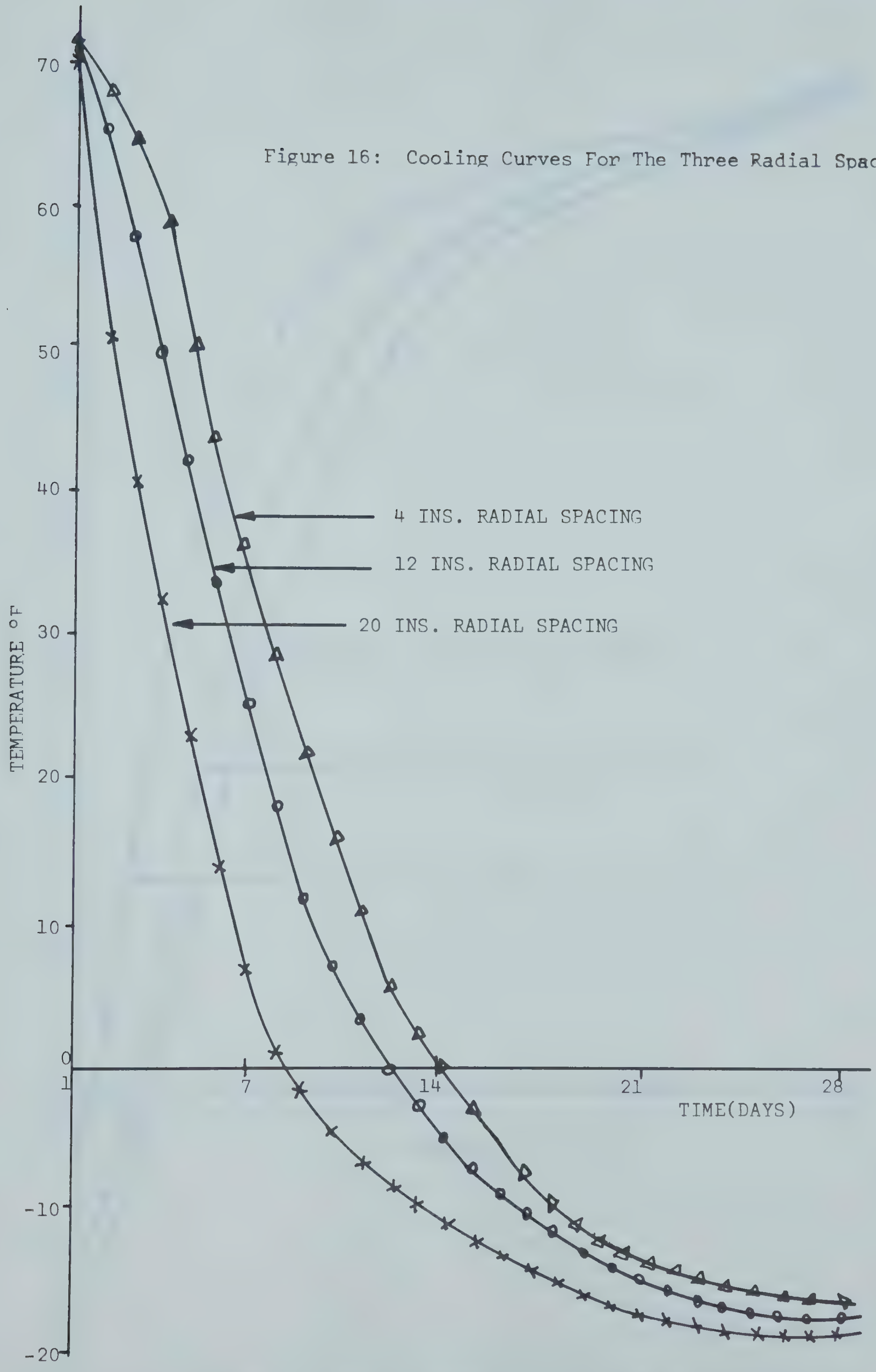


Figure 16: Cooling Curves For The Three Radial Spacings.

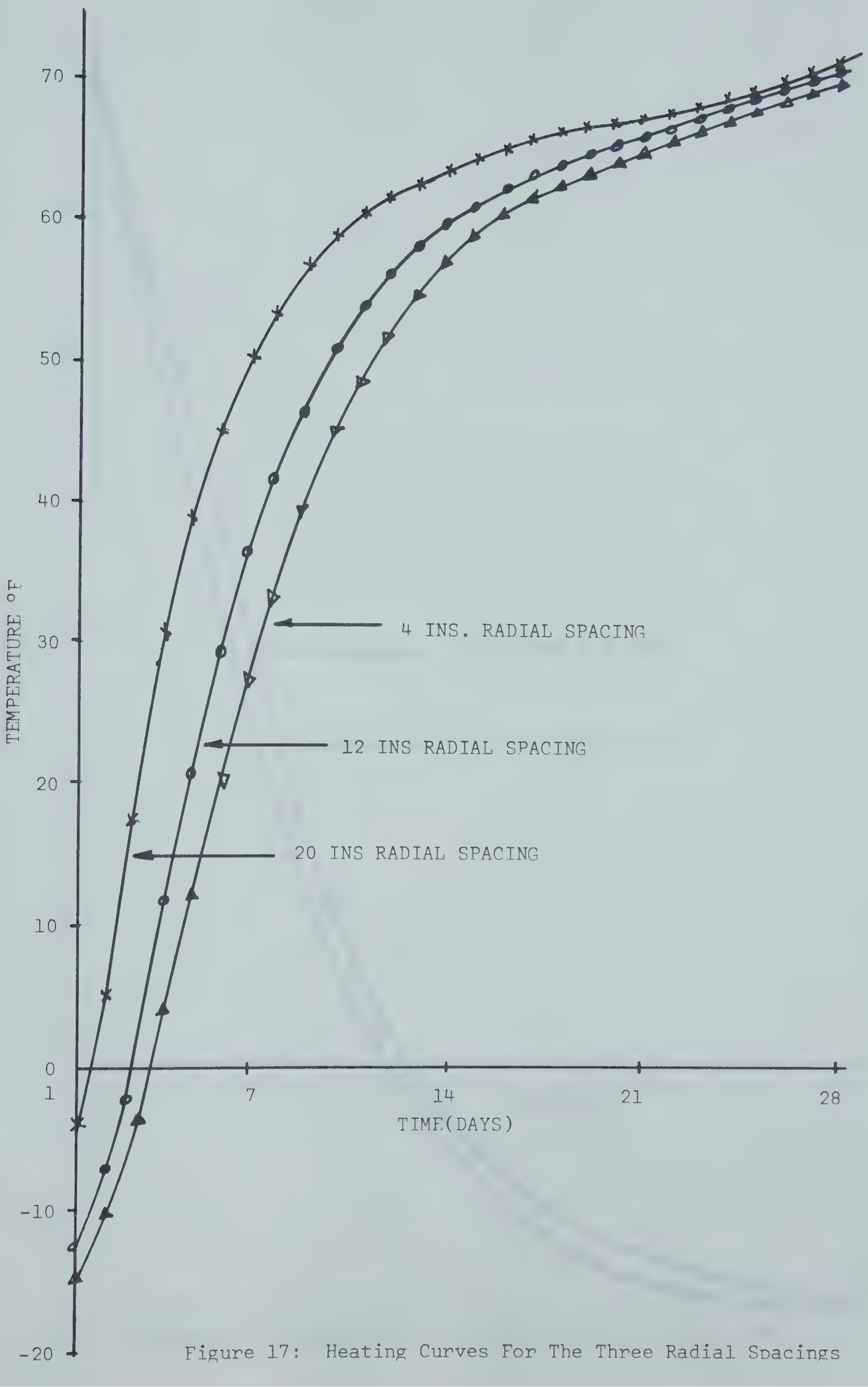


Figure 17: Heating Curves For The Three Radial Spacings

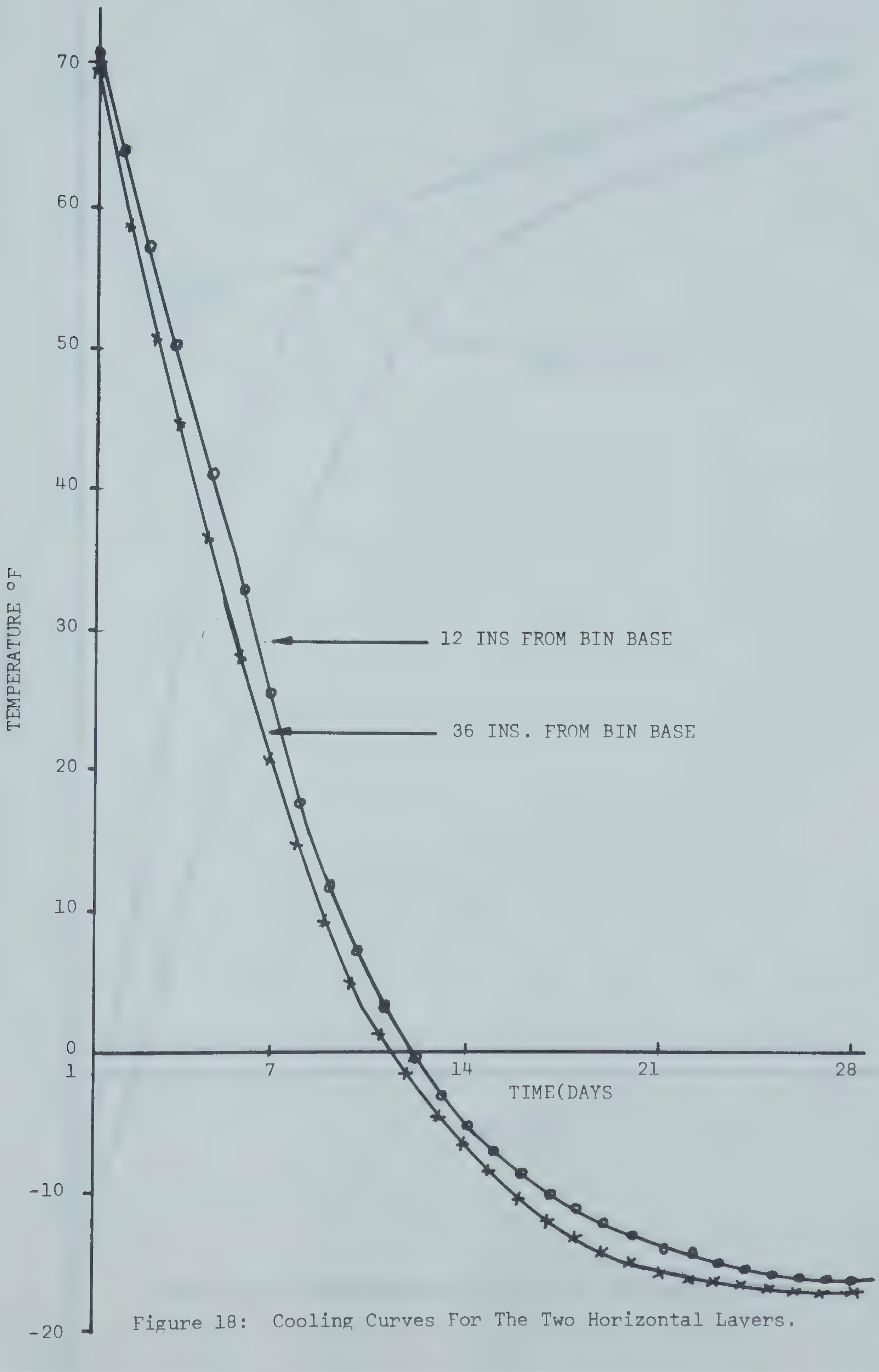
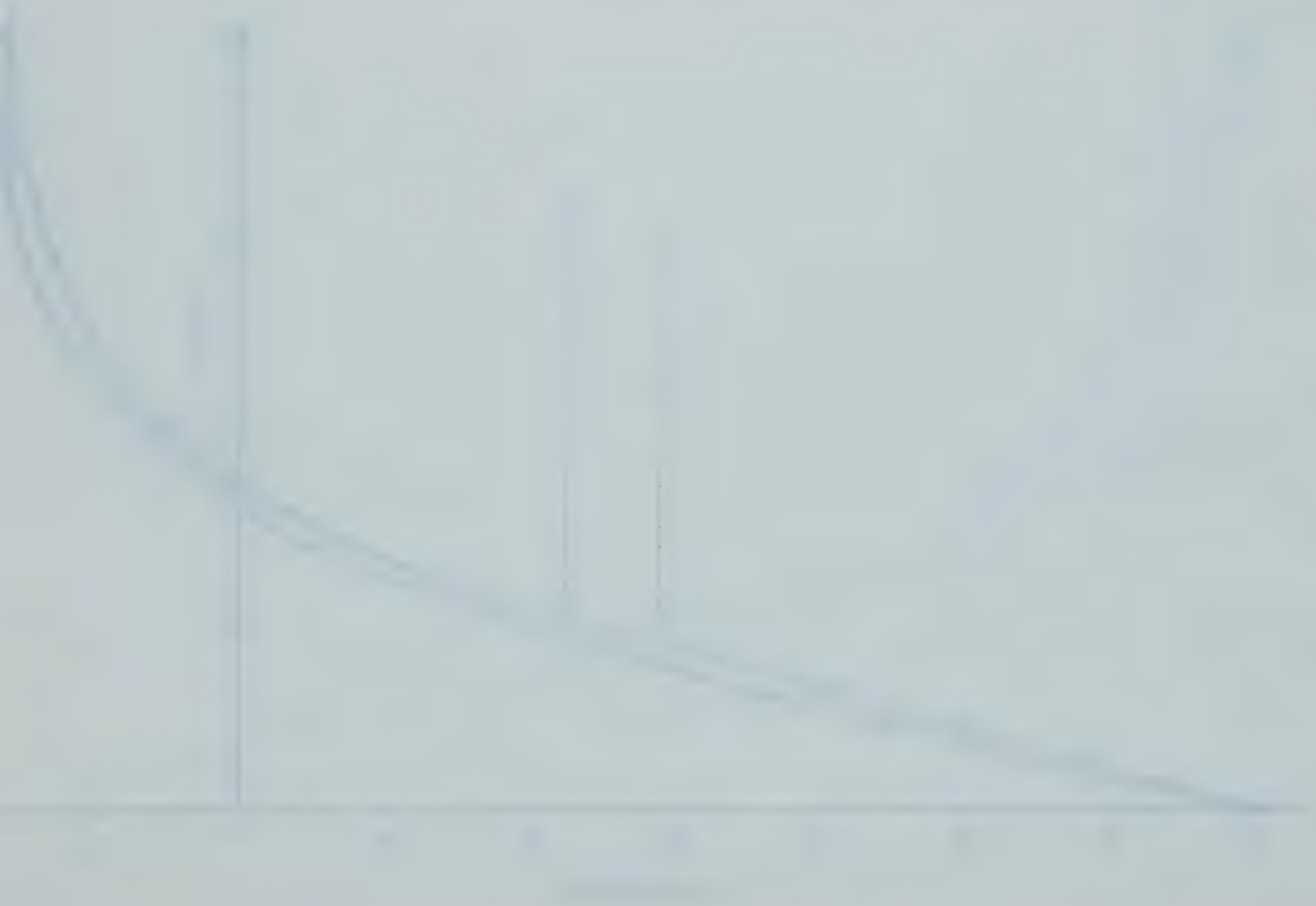


Figure 18: Cooling Curves For The Two Horizontal Layers.



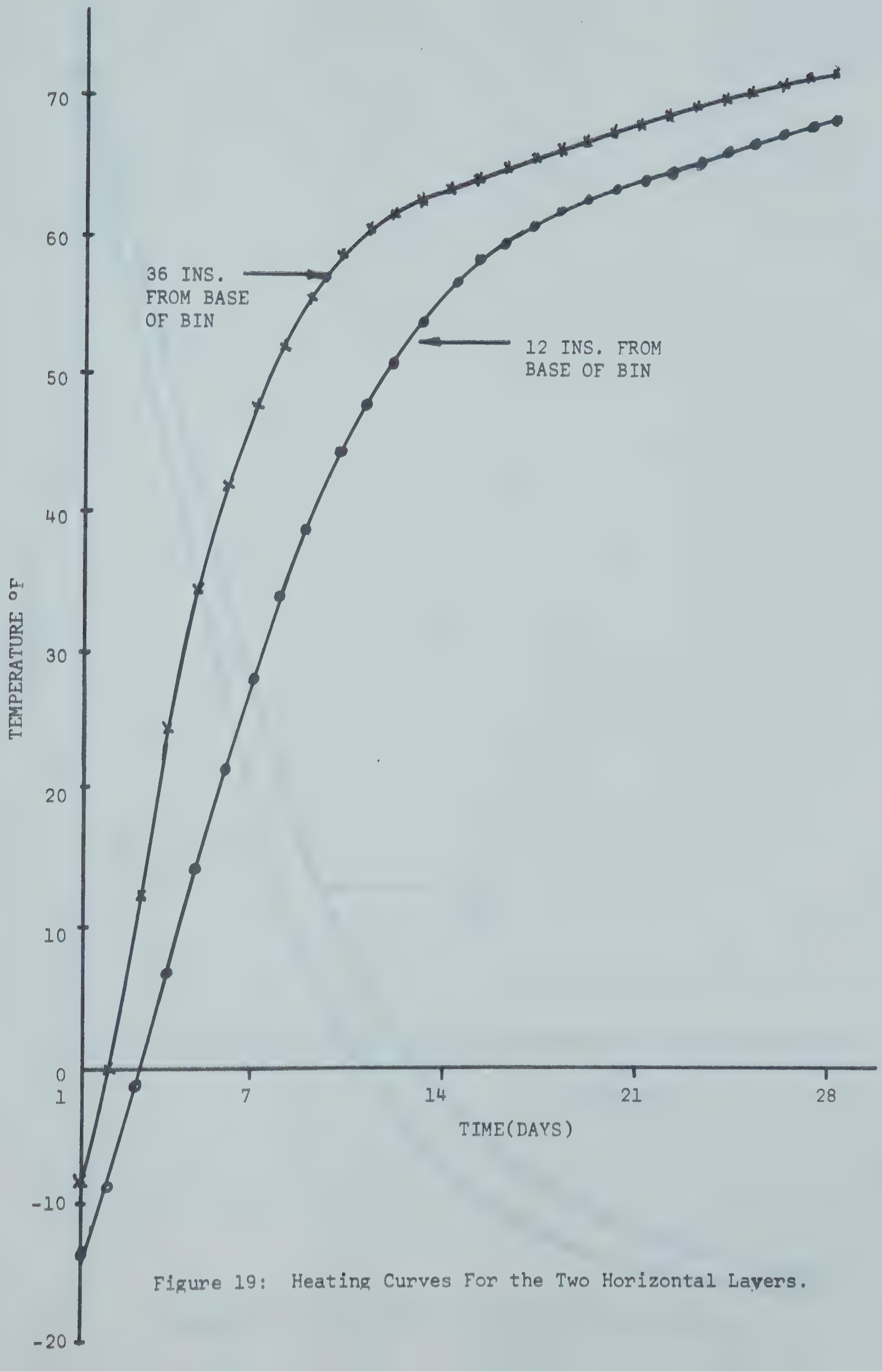


Figure 19: Heating Curves For the Two Horizontal Layers.

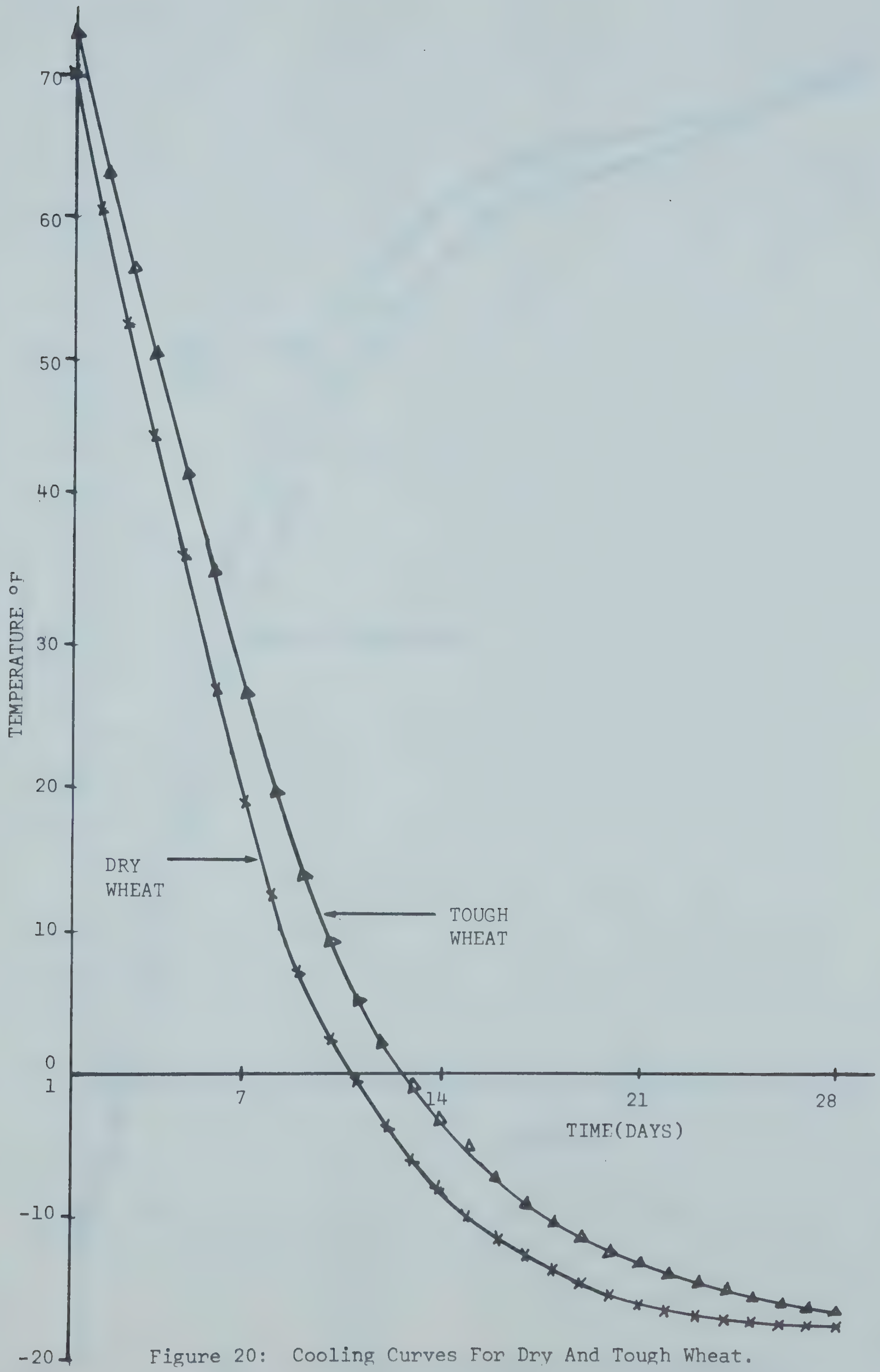


Figure 20: Cooling Curves For Dry And Tough Wheat.

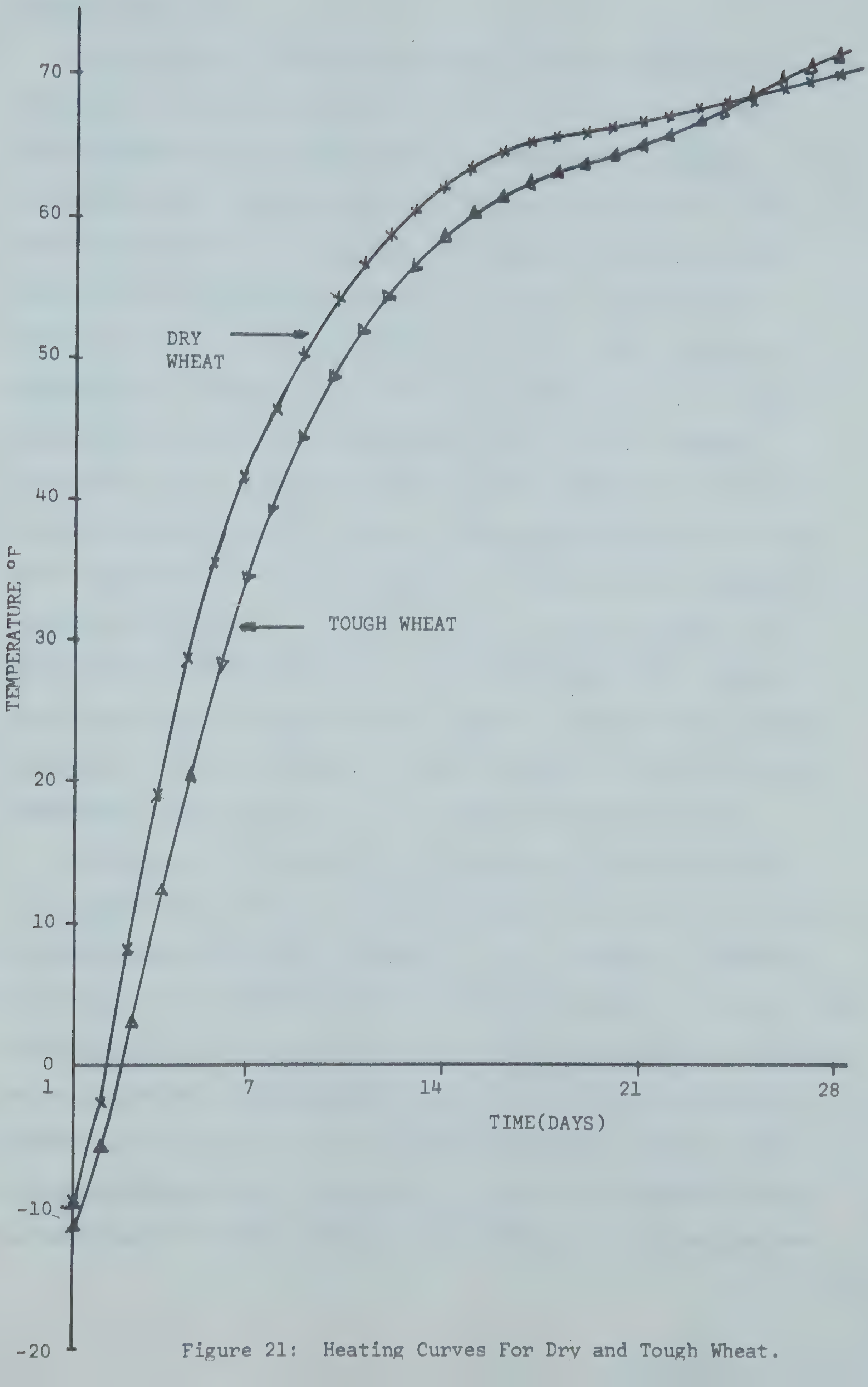


Figure 21: Heating Curves For Dry and Tough Wheat.

reached about 70°F.

The interaction of moisture and layer (LM) was significant in cooling but not during warming, and that of spacing and layer (SL) was significant during warming but not in cooling. The graphs illustrating these interactions are given in Figures 22 to 25. The interactions are due to a differential response depending upon the combination of the factors. As shown by Figure 22 the difference between dry wheat (low moisture) and tough wheat (high moisture) is much greater at the upper layer than at the lower layer for cooling. During warming the dry and tough wheat showed identical response (Figure 23). Thus during cooling the effects of moisture and layer were not independent of each other. During warming moisture and layer acted independently. During warming the different radial spacings also responded differently at the upper and lower layers resulting in an interaction which was significant when tested (Figure 24). However, the different radial spacings showed identical response during cooling (Figure 25). Thus the effects of radial spacings and layers were not independent during warming but were independent during cooling.

Interaction of radial spacing and moisture (Figures 26 and 27) was non-significant during cooling and warming. Therefore, the effects of spacing and moisture were independent. The interaction, Spacing x Moisture gave the temperature gradient along the radius of the bin. The central portion of the grain had higher temperatures than the periphery at the end of the cooling period (Figure 26). The lowest temperature recorded at the end of the 28 day cooling period was -19°F with the highest temperature -15°F (Appendix I). The lowest temperature was in the periphery of the dry wheat and the highest in the central portion

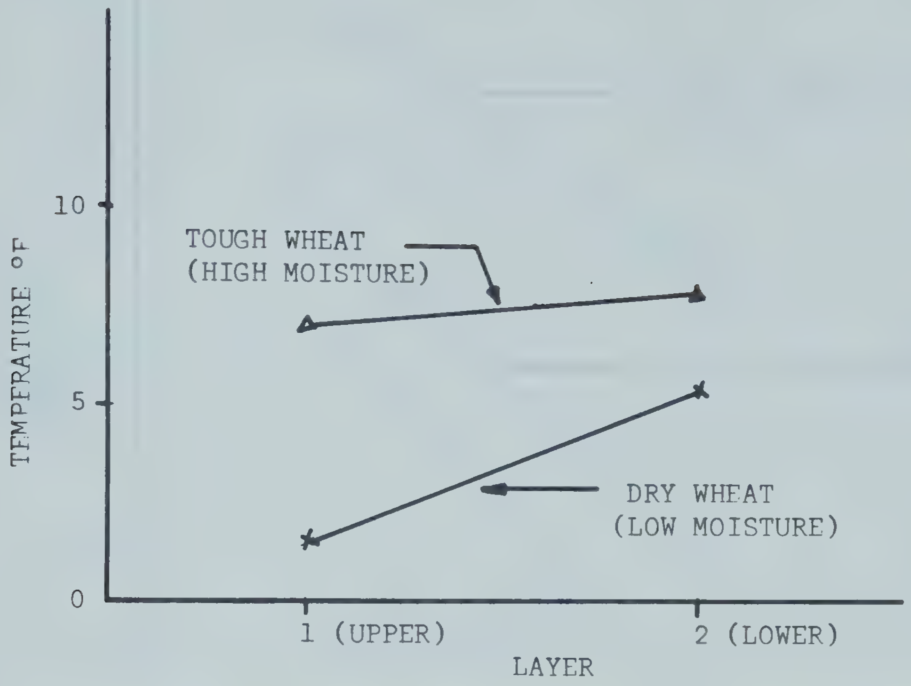


Figure 22: Graph Illustrating The Interaction Of Moisture and Layer (Cooling)

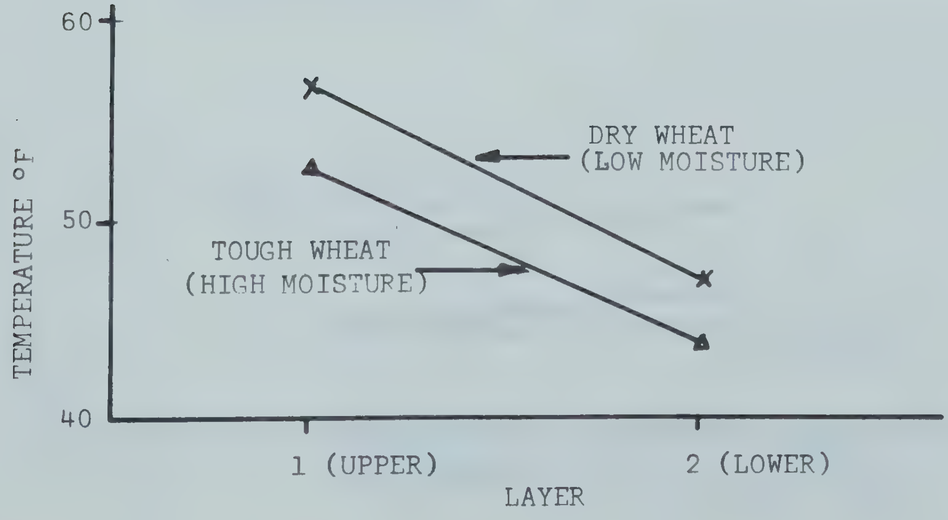


Figure 23: Graph Illustrating The Lack Of Interaction Of Moisture And Layer (Warming)

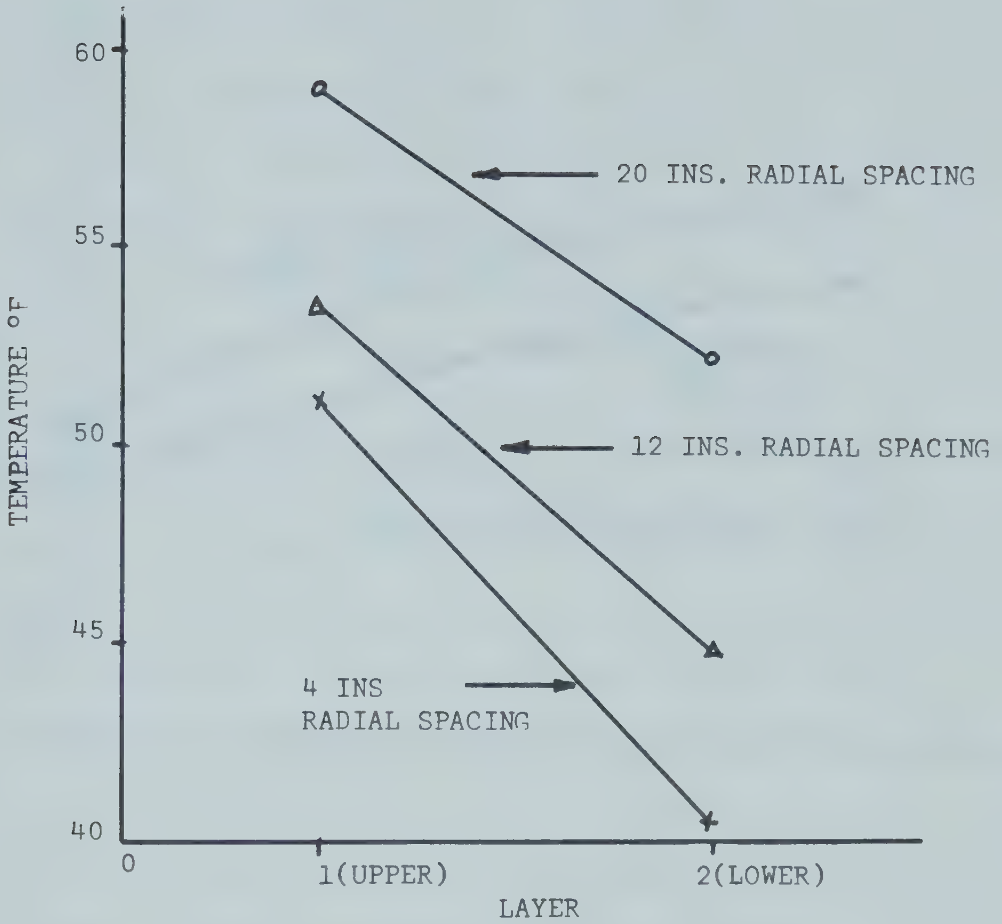


Figure 24: Graph Illustrating The Interaction Of Radial Spacing And Layer (Warming)

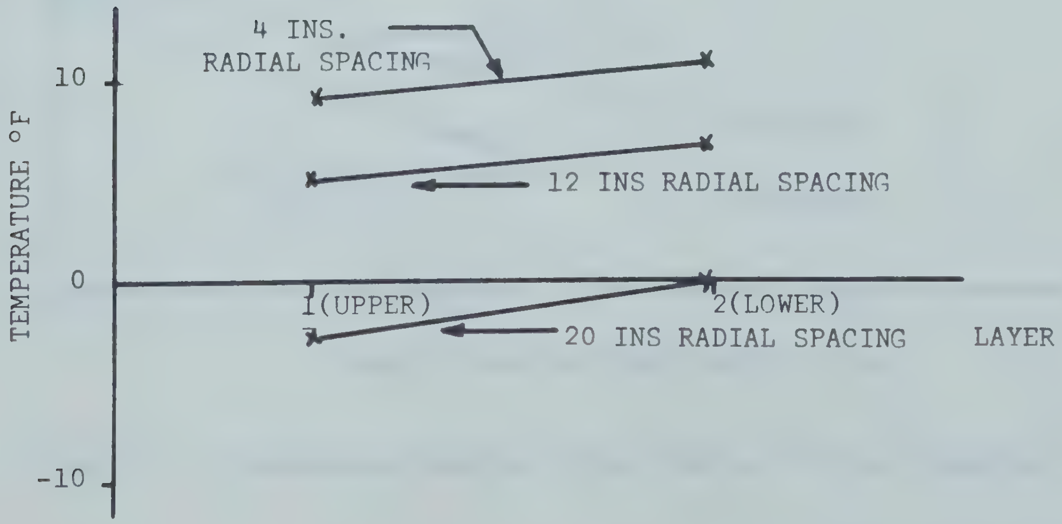


Figure 25: Graph Illustrating The Lack Of Interaction Of Radial Spacing And Layer (Cooling)

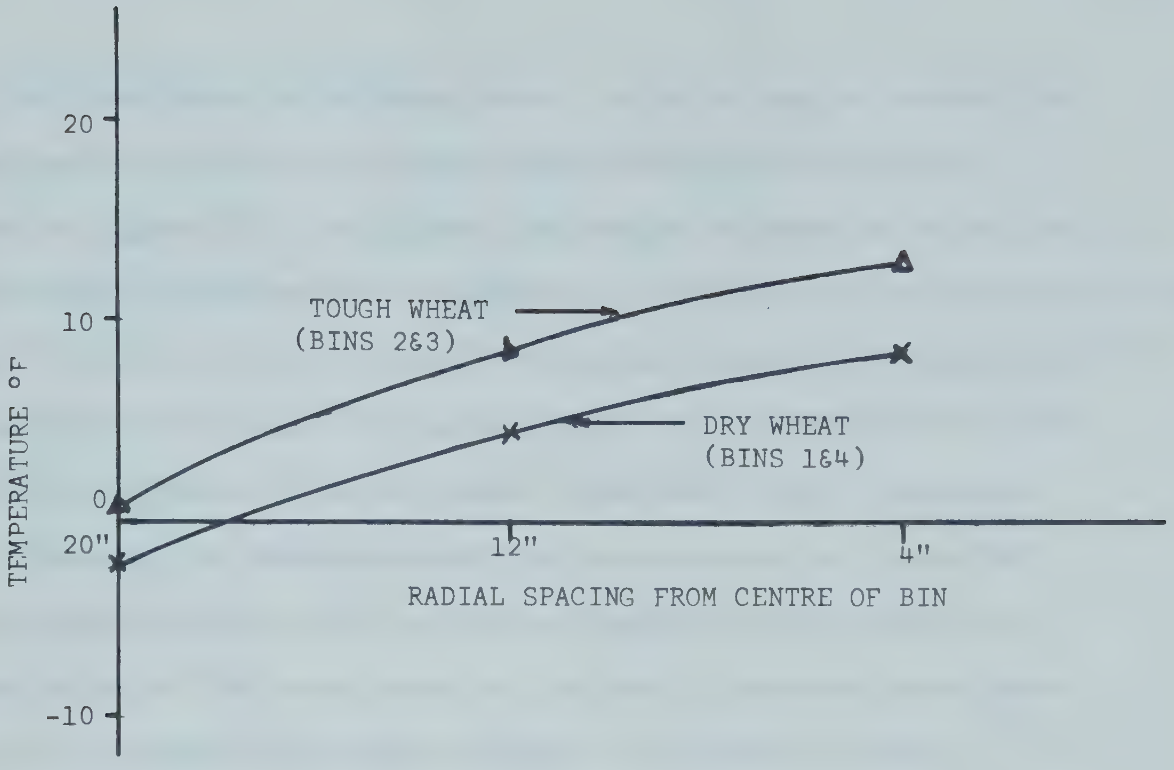


Figure 26: Temperature Gradient Along Radius Of Bins (Cooling)

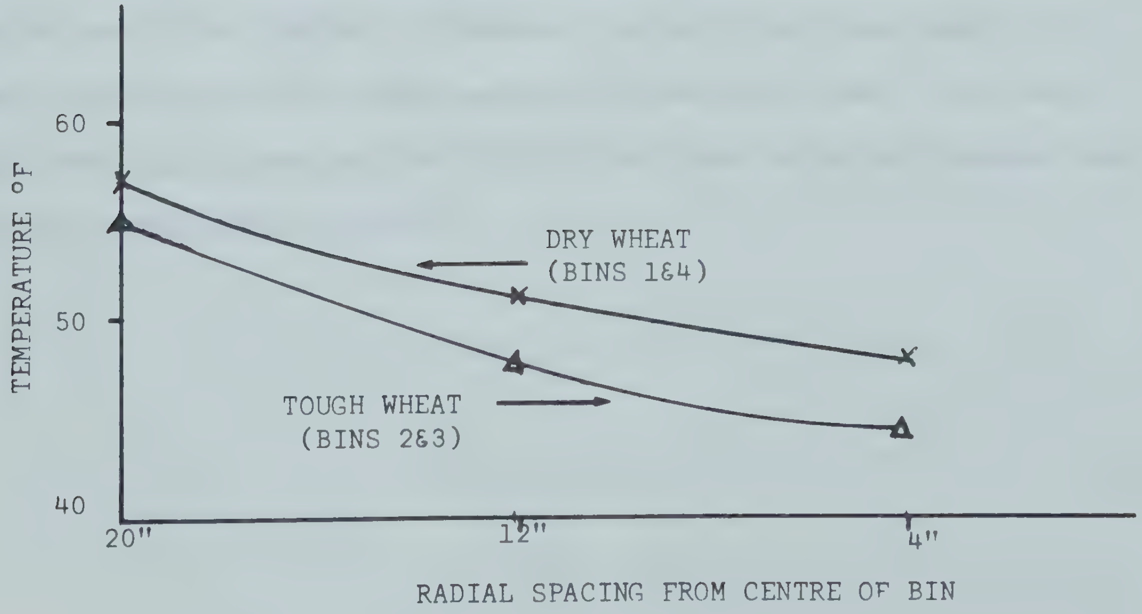


Figure 27: Temperature Gradient Along Radius Of Bins (Warming)

of the lower layer in the tough wheat. After 28 days of warming, the periphery of the grain had higher temperatures than the central portion (Figure 27). The highest temperature recorded at the end of the warming period was 89°F (Appendix I), this occurring at the centre of the upper level in the tough wheat. The highest temperature indicated the creation of hot spots. The lowest temperature was 68°F at the centre of the lower level in the dry wheat after the 35 days of warming.

Although the interactions within moisture were not tested for significance as this would require an assumption, bins having the same moisture (B/M) were tested to find out if there was significant variation between bins within moisture. In order to do this, variation due to three- and four- factor interactions within moisture were assumed to be zero, so that any variation was due to error. The sum of squares of these interactions were added and the value divided by the sum of the degrees of freedom to obtain a new mean square. The mean square of B/M was tested against the new mean square. The test indicated significant but not highly significant variation between bins of the same moisture content.

Multiple Linear Regression

The cooling and heating curves of dry and tough wheat (Figures 20 and 21) indicated distinct relationships between grain temperature and time. Therefore it was desirable to express these relationships in a mathematical form and this was done by using Multiple Linear Regression. Calculation of the Multiple Linear Regressions was performed using a program of the University of Alberta Computing Centre.

Results of the Regression Analysis

The results of the Multiple Linear Regression program are given in Tables 10 to 13.

The regression equation which gave the best fit had the following general form:

$$Y = a + bX + cX^2 + dX^3$$

where Y = the average grain temperature in °F

X = time in days

a = constant

b, c, d = multiple partial regression coefficients.

The regression coefficients b and d have negative signs during cooling while b has a negative sign during heating. The sign of the constant a is positive during cooling but negative during warming. As shown by the values in Tables 10 to 13 the regression coefficients and therefore the equations differ for each of the moisture and environmental temperature conditions.

The analyses of variance shown in Tables 10 to 13 indicated that the F values were significant at .01 level. Thus, the reduction in sum of squares due to regression was highly significant. The multiple correlation, R, was 0.97 for the dry wheat and 0.96 for the tough

wheat during cooling and 0.94 for the dry wheat and 0.95 for the tough wheat during heating. The multiple correlation coefficients obtained therefore indicated a very good relationship between grain temperature and days.

The pairs of observed and predicted temperature values were plotted as shown in Figures 28 to 31.

Table 10: Analysis Of Variance For The Regression (Dry Wheat Under Cooling Condition)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
Attributable to regression	3	230908.44	76969.44	1705.10**
Deviation from regression	332	14986.69	45.14	
Total	335	245895.13		

Regression Equation:

$$Y = 83.39539 - 12.18595\ X + 0.49709\ X^2 - 0.00684\ X^3$$

Multiple Correlation: 0.97

Table 11: Analysis Of Variance For The Regression (Tough Wheat Under Cooling Condition)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OR SQUARES	MEAN SQUARES	F VALUE
Attributable to regression	3	240386.75	80128.88	1458.51**
Deviation from regression	332	18239.75	54.94	
Total	335	258625.50		

Regression Equation:

$$Y = 83.06989 - 10.34647 X + 0.35827 X^2 - 0.00412 X^3$$

Multiple Correlation: 0.96

Table 12: Analysis Of Variance For The Regression (Dry Wheat Under Warming Condition)

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
Attributable to regression	3	172392.94	57464.31	838.30*
Deviation from regression	332	22758.19	68.55	
Total	335	195151.13		

Regression Equation:

$$Y = -22.64201 + 12.68632\ X - 0.60253\ X^2 + 0.00963\ X^3$$

Multiple Correlation: 0.94

Table 13: Analysis Of Variance For The Regression
(Tough Wheat Under Warming Condition)

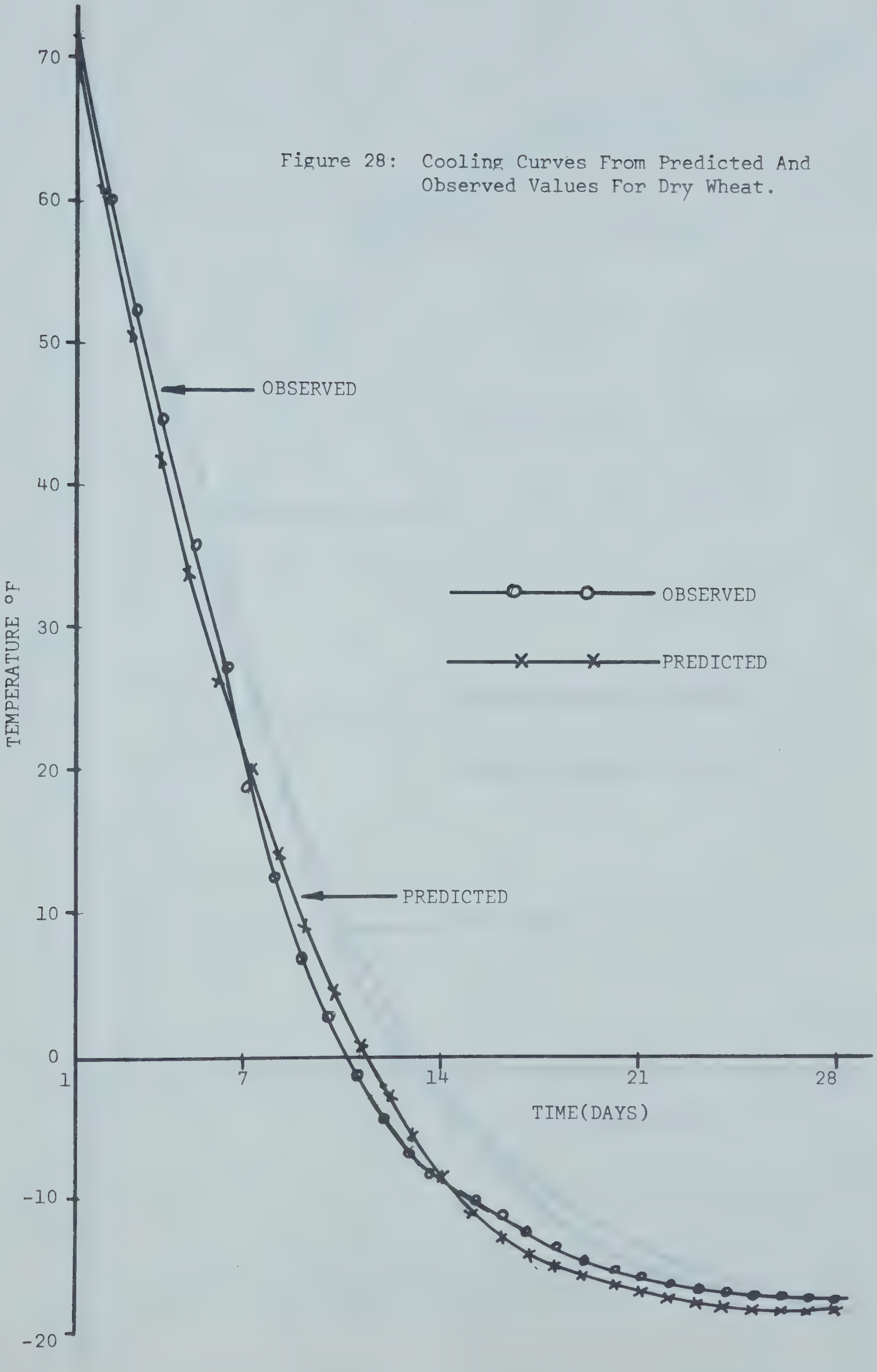
SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
Attributable to regression	3	192168.25	64056.08	1004.97**
Deviation from regression	332	21161.38	63.74	
Total	335	213329.63		

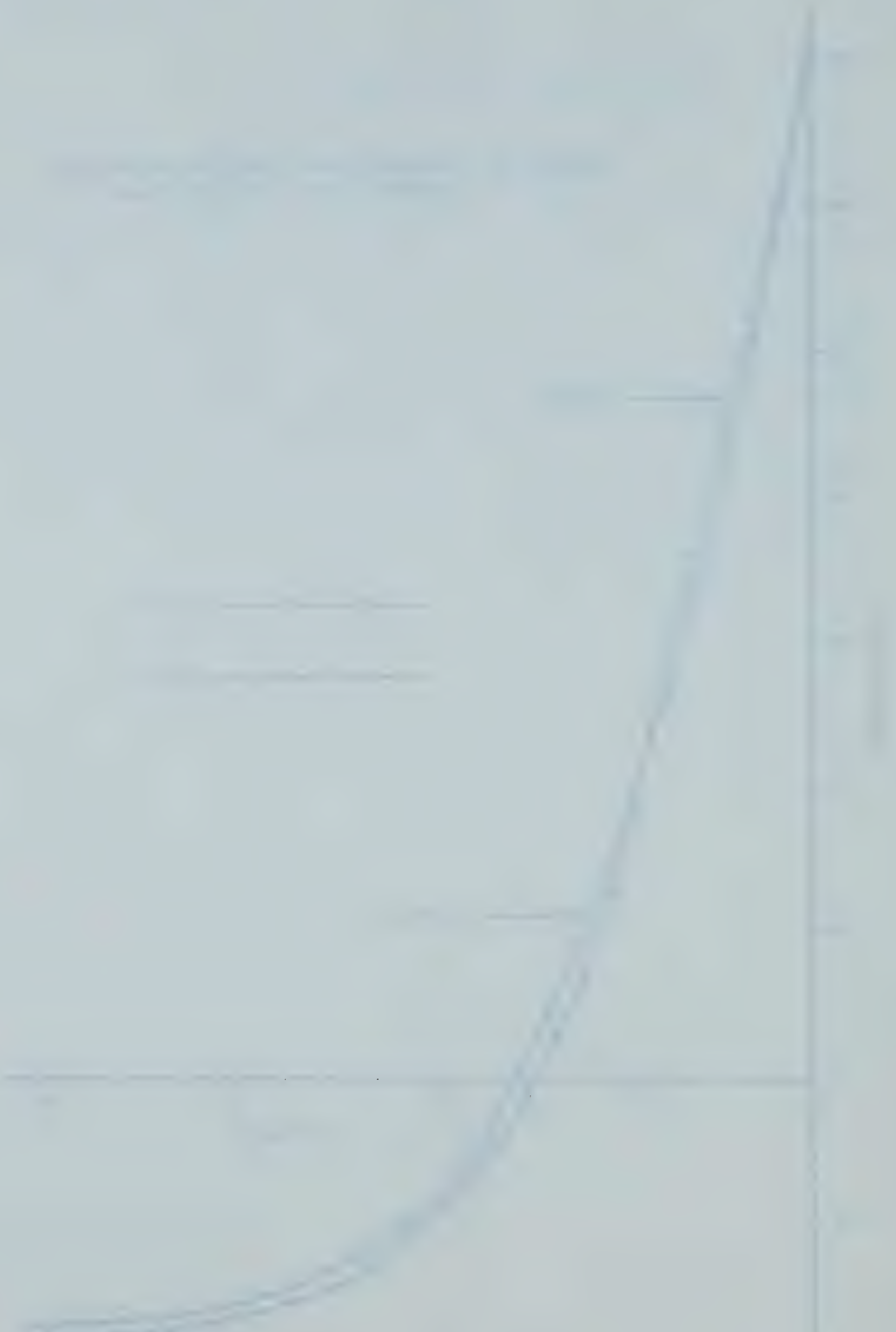
Regression Equation

$$Y = -24.88045 + 11.53824\ X - 0.50674\ X^2 + 0.00779\ X^3$$

Multiple Correlation: 0.95

Figure 28: Cooling Curves From Predicted And Observed Values For Dry Wheat.





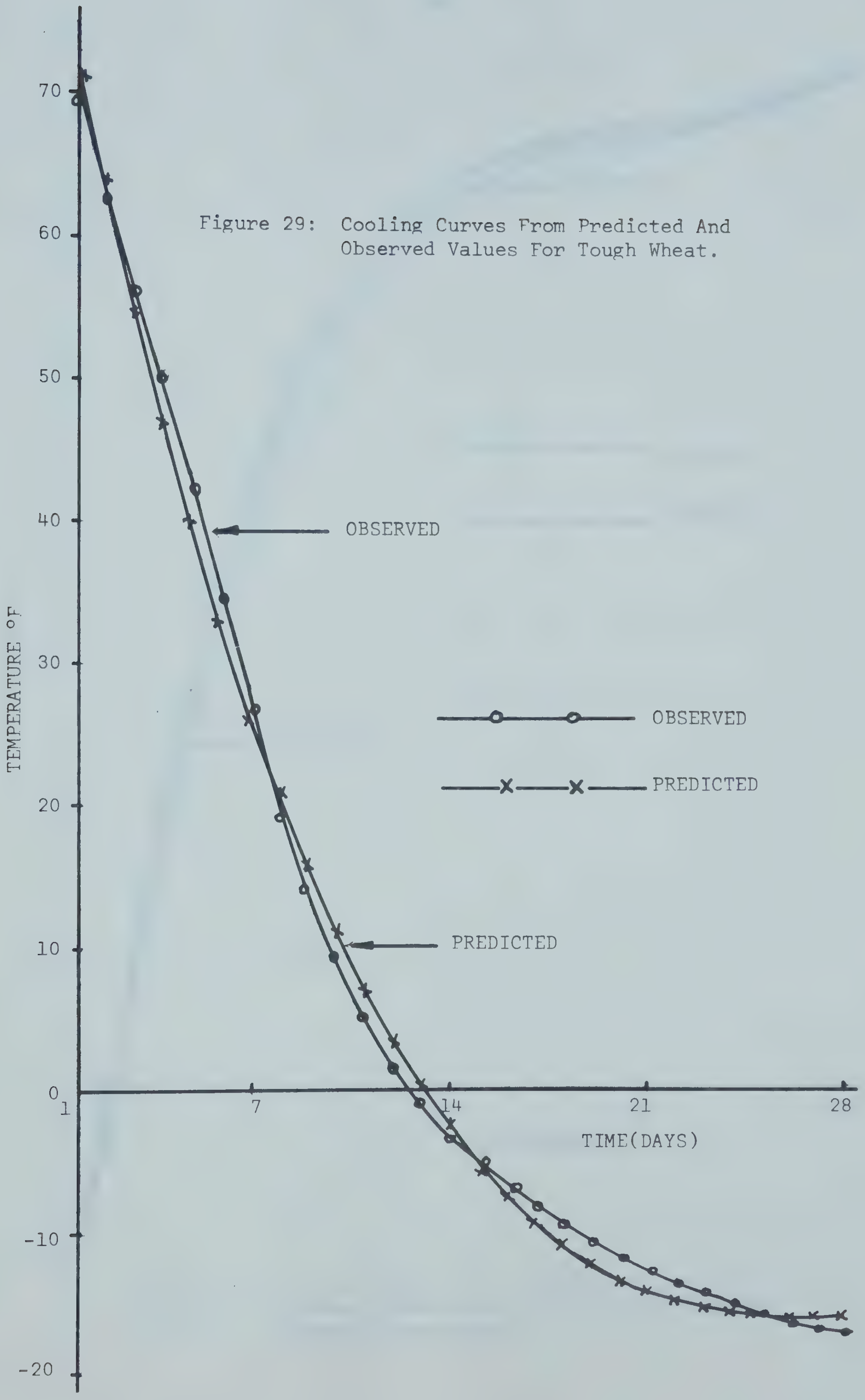


Figure 29: Cooling Curves From Predicted And Observed Values For Tough Wheat.

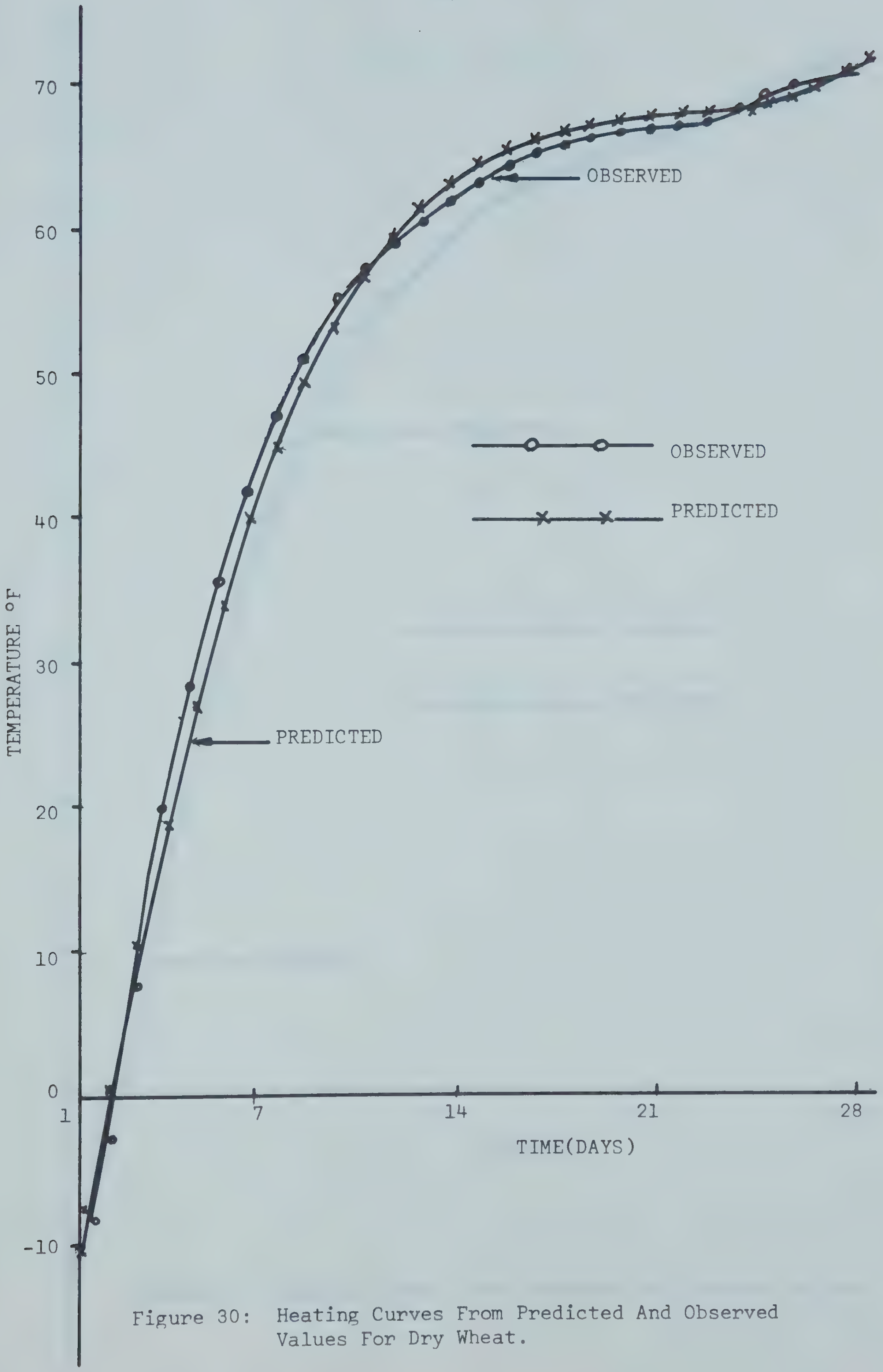


Figure 30: Heating Curves From Predicted And Observed Values For Dry Wheat.

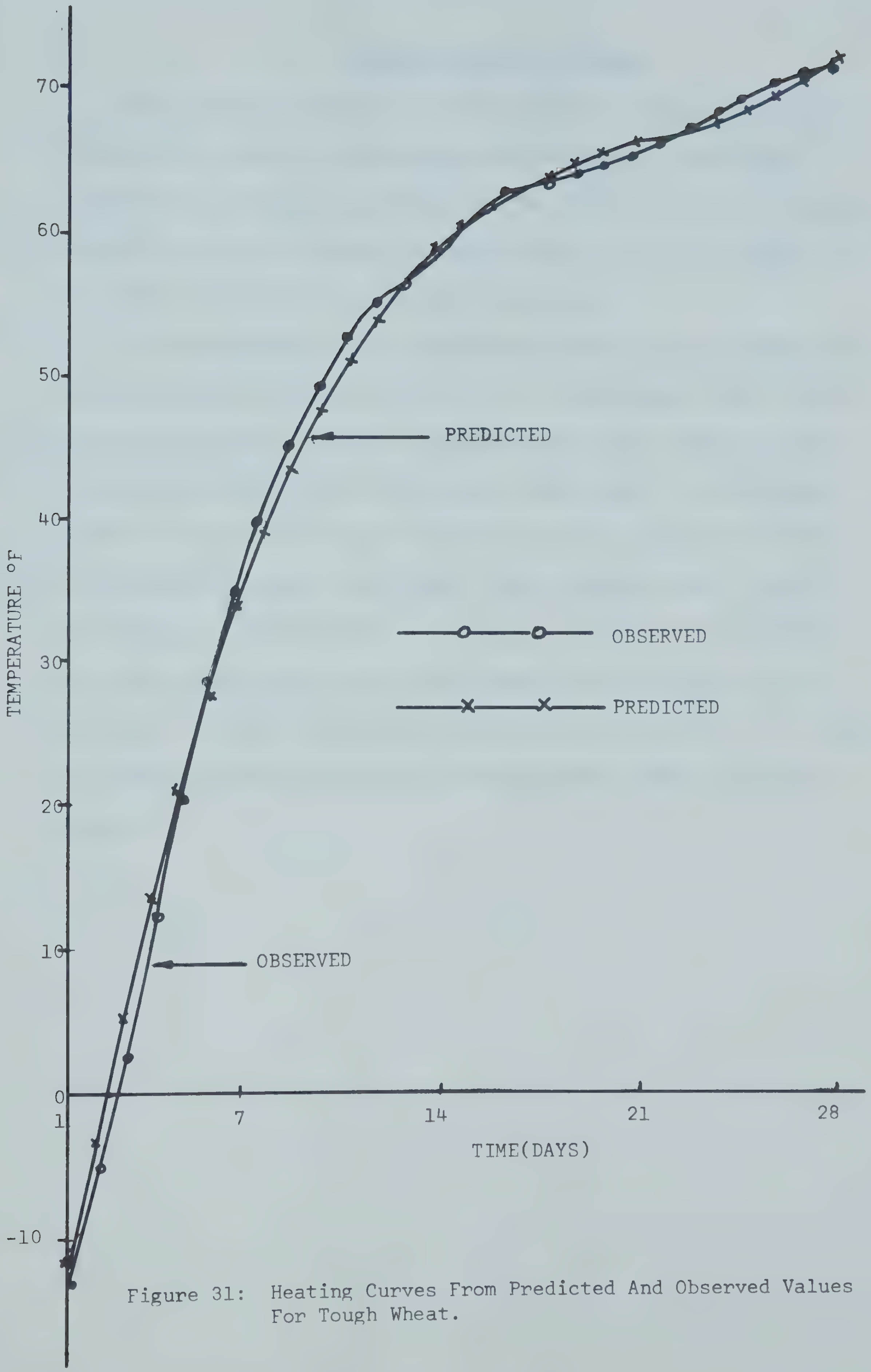
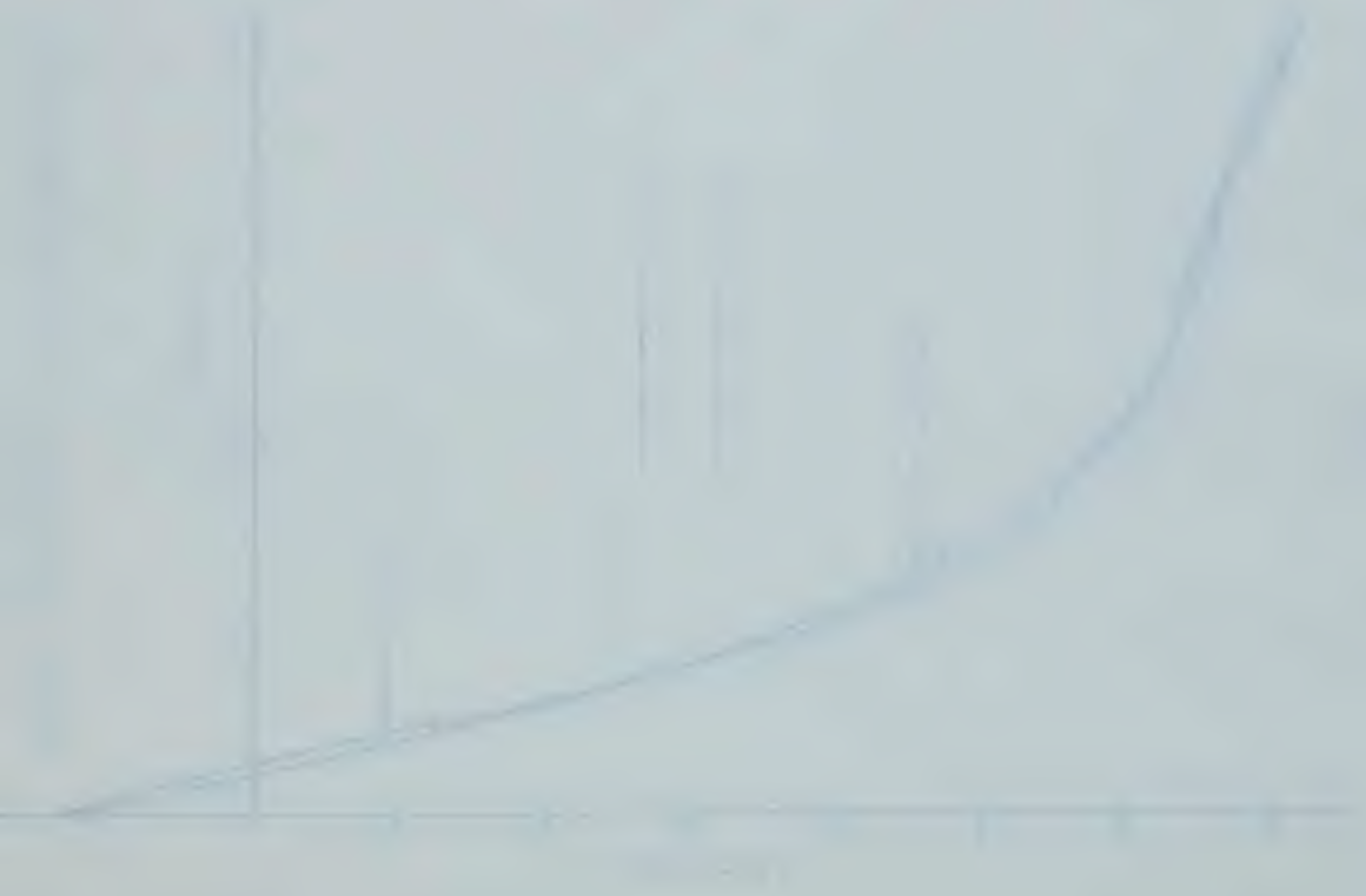


Figure 31: Heating Curves From Predicted And Observed Values For Tough Wheat.



Moisture Content of Grain

The moisture contents of the dry and tough wheat from samples taken at the various thermocouple positions at the end of the experiment are shown in Appendix II. The initial and final average moisture contents of the dry and tough wheat are shown in Table 14. The range of moisture contents are also given.

At the beginning of the experiment the dry and tough wheat had average moisture contents of 11.35% and 16.46% respectively. After cooling followed by warming, the upper levels gave slightly higher moisture contents in both the dry and tough wheat. In the tough wheat, the upper levels gave moisture contents above 17.00% while the moisture contents in the lower levels were all below 17.00%. The average moisture content at the upper level in the dry grain was above 11.00% while that of the lower level was below 11.00%. This would indicate that some redistribution of moisture in the wheat had occurred during the period, with migration towards the upper layers.

Table 14: Moisture Contents (Percentage Wet Basis)

Moisture Content	Wheat			
	Dry (Bin 1)	Dry (Bin 4)	Tough (Bin 2)	Tough (Bin 3)
Average Initial	11.35	11.35	16.46	16.46
Range	10.80-11.60	10.80-11.60	15.80-17.00	15.80-17.00
	(0.80)	(0.80)	(1.20)	(1.20)
Average Final	11.03	11.11	16.85	16.86
	10.40-11.70	10.25-11.70	16.00-17.70	16.20-17.70
	(1.30)	(1.45)	(1.70)	(1.50)
Average				
Final at Upper Level	11.11	11.45	17.37	17.11
Range	10.40-11.70	10.20-11.70	16.70-17.70	16.60-17.70
	(1.30)	(1.50)	(1.00)	(1.10)
Average				
Final at Lower Level	10.96	10.66	16.33	16.60
Range	10.40-11.60	10.25-11.00	16.00-16.75	16.20-16.95
	(1.20)	(0.75)	(1.75)	(1.75)

Final Condition of the Wheat

Results from microbial analysis and germination counts are given in Appendix III together with temperatures and moisture contents at the points of sampling at the end of the experiment.

At the start of the experiment, the wheat showed no spoilage with 90-95% germination. Microbial analysis showed an average of 49% grain yielding *Fusarium sp*, 28% *Alternaria sp*, 8% *Penicillium sp*, 3% *Aspergillus sp*., 4% *Mucor sp* and 16% *Rhizopus sp*. High germinability, substantial amounts of *Alternaria* and traces of *Penicillium* are attributes of normal sound grain[35]. At the end of the experiment, the upper portion of the tough wheat showed complete and intermediate spoilage with 0 - 25% germination and occurrence of 72 - 100% infestation of either *Penicillium* or *Aspergillus*. The frequency of *Penicillium sp* and *Aspergillus sp*, which are indicators of deterioration[12,35], was lower in the dry grain and the lower level of the tough wheat, being 0 - 54%. The lower level of the tough wheat showed 50 - 75% germination, and the dry wheat 70 - 89% germination at both levels. Thus though the tough and the dry grain showed deterioration, the tough wheat showed more spoilage than the dry wheat.

DISCUSSION OF RESULTS

Temperature

The effect of the environmental temperature on the grain temperature is given by the response of the grain temperature to the external temperature. In this response, grain temperature dropped and began to stabilise as the cold temperature of the environment was approached. During warming, the grain temperature continued to rise after the temperature of the environment had been attained. The increase in microbial population at the end of the experiment indicated that during warming microbial activity interfered with the tendency of the grain temperature to stabilise.

As shown by the cooling and heating curves (Figures 20 and 21) the difference between dry and tough wheat is small at the beginning of cooling or heating. The difference increases as either cooling or heating continues and then decreases as the environmental temperature is attained. This may be due to the tendency of the grain temperature to stabilise at the environmental temperature.

For the levels of radial spacing, the difference between the 20 ins. and 12 ins. radial spacing was greater than that between those at 12 ins. and 4 ins. spacing for both cooling (Figure 16) and heating (Figure 17). This follows from the result that the wheat at the 20 ins. radial position cooled and warmed significantly faster than the wheat at the 12 ins. and 4 ins. radial spacing and that wheat at 12 ins. radial spacing cooled and warmed faster than wheat at the 4 ins. radial spacing.

The effect of layer (height) was highly significant during warming but although significant not highly significant during cooling (Tables 8 and 9). The interaction of day and layer was

much greater during warming than cooling as shown in Figures 18 and 19 and as shown by F values in Tables 8 and 9. These observations suggest that during warming the upper layers of the grain warm very quickly causing a larger variation than in cooling.

Although the dry and tough wheat cooled and warmed up under the same conditions, there was a significant difference between the two moisture levels in heating and cooling. This difference may be in part due to water having a high specific heat. However, the non-significance of the Spacing x Moisture interaction indicated that the effects of moisture are the same for each level of spacing.

The cooling and heating behaviour is an indication of what happens in stored wheat during winter and spring. When the grain temperature is below about 60°F hot spots do not develop readily in either tough or dry grain. Above this temperature range, hot spots would probably develop readily in tough grain as a result of suitable temperature conditions for microbial growth. Thus in spring, grain condition may deteriorate very quickly.

When the mass is not very great, there could be a gradual but steady heating of the whole mass of grain without development of pronounced hot spots. Normally the central portion would be expected to heat more than the periphery.

Cubic functions were found to fit the rate of cooling and the rate of heating of the dry and tough wheat. The equations are considered to hold within the range of values used in their determination. For the types of grain used and the period involved,

the temperature of the grain can be predicted from the regression equations. Such regression equations established for practical storages would enable prediction of grain temperature under such storage.

Moisture Content

Hall[19,20] reports that when grain is placed in storage when the grain is warm, as in the fall, the air in the grain near the surface of the storage cools and moves down along the edge of the bin, across the bottom and then up, near or at the centre of the bin where the air and grain are warm. The air moving through the centre of the bin picks up moisture until it leaves the bin or moves across the top to the sides. At this location the surface of the grain is cold and the moisture condenses on the grain, thus raising its moisture content. The moisture may also raise the relative humidity in the intergranular spaces without condensation, with subsequent rise in the grain's moisture content. The resultant moisture accumulation at the top leads to spoilage (Figure 32). If the grain is cold when placed in the bin as in the winter, the air currents rise along the surface edge of the bin during later winter and early spring. The currents move down through the centre of the bin to the bottom where moisture condenses on the cold bottom. The air then moves to the walls and up along the walls being heated. Thus the grain spoilage resulting from moisture accumulation occurs at the bottom of the grain as illustrated diagramatically in Figure 33.

In this experiment, the storage began as warm grain with a cold

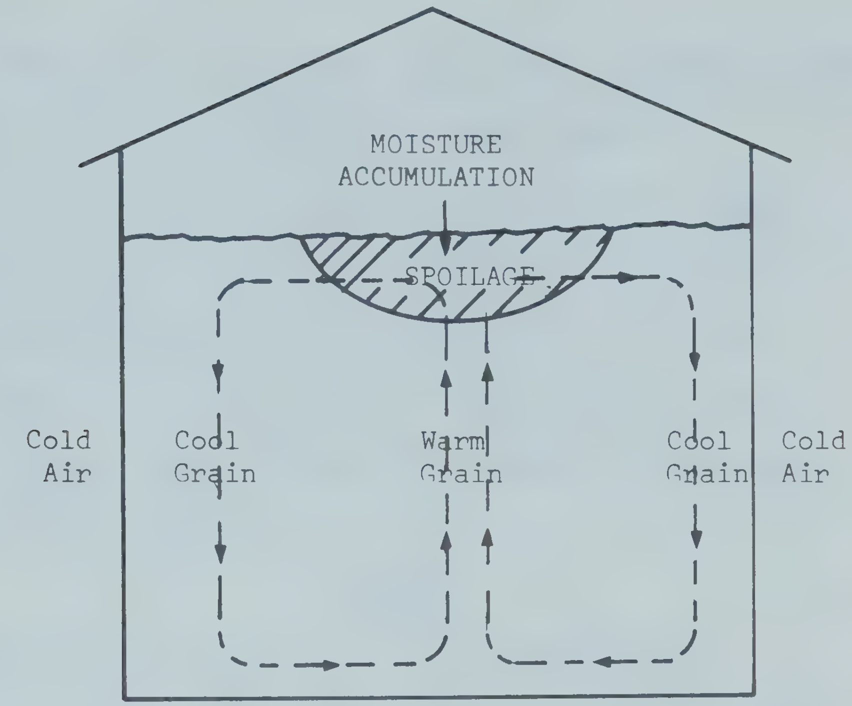


Figure 32: Convection Air Currents With Warm Grain In Bin With Colder Surrounding Air[19].

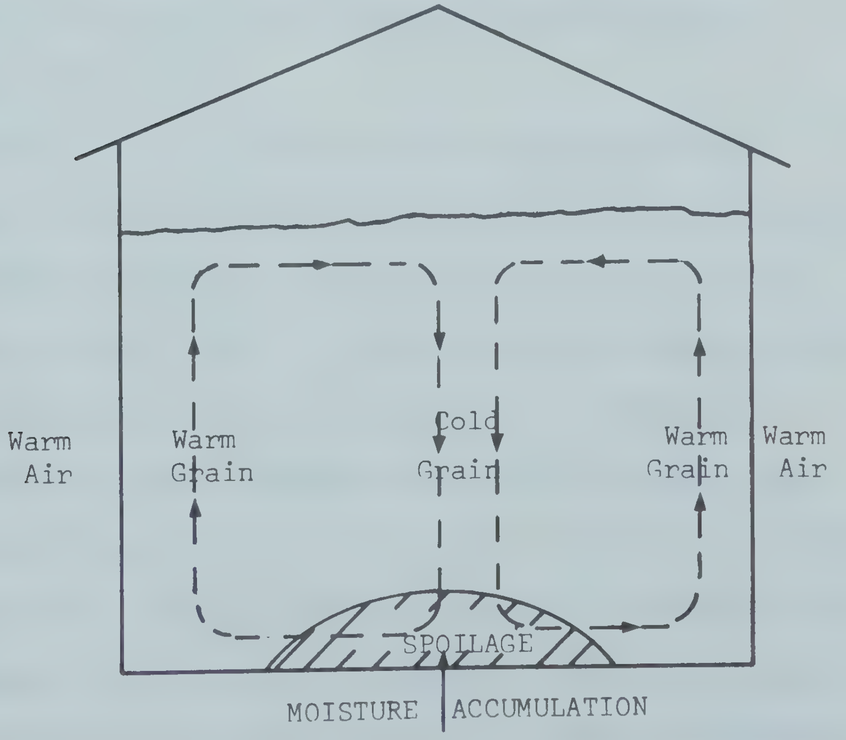


Figure 33: Convection Air Currents With Cold Grain In Bin With Warmer Surrounding Air[19].

environment, continued as cold grain with a warm environment, and ended as grain with central temperature higher than the environment. Thus, though the final moisture tests and fungal analysis showed the first condition (Figure 32) the moisture accumulation and spoilage could be a combination of the two.

To investigate this aspect further would require moisture measurements in situ during storage and a study on the effect of chilling on the development of hot spots.

Comment

The results of the experiment should be valuable in:

1. Predicting time-rate of cooling and heating in dry and tough grain in unventilated storage. This, instead of repeated readings on the vertical axis of grain bins, would give a good general indication of the grains' fitness for storage.
2. Indicating the behaviour of grain temperature with respect to spoilage when stored during winter and spring. A better understanding of this behaviour would lead to measures being taken that would prevent or reduce losses.
3. Providing information necessary for the refrigerated storage of grain. Refrigeration offers both short term and long term possibilities for safe storage of tough and damp grain. Moisture content is one of the factors that affects the time interval required to produce cooling. A knowledge of the cooling behaviour of grain of different moisture contents is essential for efficient use of refrigeration equipment.

CONCLUSIONS

The conclusions from the project are :

1. Temperature differentials are established in grain under the influence of external temperatures. Under cooling conditions, the temperature differentials tend to stabilise as the temperature of the environment is approached. There is no tendency to stabilization under warming condition and this is attributed to microbial activity.
2. The temperature differentials established are affected significantly by time, height from bin-base, spacing from vertical axis and moisture content.
3. Different rates of cooling and heating occured at the three radial positions. The rates were faster at the outer than at the inner positions. The differences among them were significant in either process.
4. The upper layer in a bulk of grain cools and warms faster than the lower layer. The difference between the rate of cooling was found to be significant but not highly significant and the difference between the rate of warming was highly significant.
5. Tough grain cools significantly slower than dry grain. Tough grain warms up significantly slower than dry grain when there is no microbial activity. At the start of microbial activity tough grain heats faster.

6. Above about 60°F grain temperature, fungi develop more readily in tough grain, leading to the creation of hot spots, than in dry grain.
7. Changes in grain temperature are accompanied by moisture re-distribution.
8. Tough grain can become completely spoiled in a short period without indication of very high temperatures.
9. Grain temperature, Y, has a distinct relationship with time, X, given by the regression equation:

$$Y = a + bX + cX^2 + dX^3$$

where Y is in °F, X in days, a is a constant and b, c and d are multiple partial regression coefficients. The equation holds for both cooling and heating.

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APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 1 (DRY WHEAT) UNDER COOLING CONDITIONS AT 9:00 A.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	70	70	71	71	71	70	70	70	71	71	70	70
2	42	64	66	65	61	55	47	65	65	68	64	46
3	30	52	60	59	52	40	34	56	58	57	51	33
4	22	43	53	49	40	33	29	47	51	50	43	28
5	12	36	46	43	33	22	16	40	44	42	34	15
6	2	26	38	34	24	12	6	30	35	33	25	5
7	- 4	17	30	27	18	5	- 1	21	27	24	17	0
8	- 7.5	10	22	20	10	0	- 6	14	20	18	10	- 4
9	-10	5	15	13.5	4	- 4	- 8	8	13	10	5	- 7
10	-11	0	9	8	1	- 6	-10	3	7	5	0	- 9
11	-12.5	- 3	4	3	- 2	- 8	-12	- 1	3	1	- 3	-10.5
12	-13.5	- 6	0	- 1	- 6	-10	-13	- 4	- 1	- 2	- 5.5	-12
13	-14	- 8	- 4	- 4.5	- 8	-11	-14	- 7	- 5	- 6	- 7.5	-13
14	-15	-10	- 6	- 7	-10	-12	-15	- 9	- 7	- 8	-10	-14
15	-16	-11.5	- 8	- 9	-12	-14	-16	-11	- 9	-10	-12	-15
16	-17	-13	-10	-11	-13	-15	-17	-13	-11	-11	-13	-16
17	-18	-14	-12	-13	-14	-17	-18	-14	-13	-14	-15	-17
18	-18.5	-15	-14	-14	-15	-17.5	-18.5	-15	-14	-15	-16	-17.5
19	-19	-16.5	-15	-15	-16	-18	-19	-16	-15	-16	-16.5	-18
20	-19	-17	-15.5	-15.5	-17	-19	-19	-17	-16	-16.5	-17	-18
21	-19	-17	-16	-16	-17	-19	-19	-17	-16	-16.5	-17	-18
22	-19	-18	-17	-17	-18	-19	-19	-18	-17	-17	-18	-19
23	-19	-18	-18	-18	-18	-19	-19	-18	-17	-18	-19	-19
24	-19	-18	-18	-18	-18	-19	-19	-18	-18	-18	-19	-19
25	-19	-18	-18	-18	-18	-19	-19	-19	-18	-18	-19	-19
26	-19	-18	-18	-18	-18	-19	-19	-19	-18	-18	-19	-19
27	-19	-18	-18	-18	-18	-19	-19	-19	-18	-18	-19	-19
28	-19	-18	-18	-18	-18	-19	-19	-19	-18	-18	-19	-19

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 1 (DRY WHEAT) UNDER COOLING CONDITIONS AT 9:00 A.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	70	70	71	71	70	70	70	70	71	71	70	70
2	46	68	70	70	63	57	57	70	70	70	68	53
3	39	58	68	67	57	53	54	65	70	69	60	40
4	33	49	62	60	42	35	36	56	64	62	51	33
5	22	42	55	52	34	22	27	49	52	55	43	23
6	12	32	48	44	25	13	15	40	49	46	33	12
7	5	23	38	35	17	6	8	30	40	38	24	5
8	0	16	29	26	10	0	2	21	32	29	16	- 1
9	- 4	9	21	18	5	- 4	- 3	14	23	21	10	- 5
10	- 6.5	4.5	14.5	12	0	- 6	- 5.5	8.5	16.5	15	5	- 6.5
11	- 9	0	9	7	- 4	- 9	- 8	4	11	9	1	- 8.5
12	-11	- 3	5	3	- 6	-10.5	-10	0	6	5	- 2	-10
13	-11.5	- 5	1	- 1	- 8	-11	-11	- 3	2	1	- 5	-11
14	-13	- 7	- 2	- 3.5	-10	-12	-12	- 5	- 1	- 2	- 6	-12
15	-14	- 9	- 4	- 5	-11	-13	-13	- 7	- 4	- 5	- 8	-13
16	-15	-11	- 7	- 8	-13	-14.5	-14.5	- 9	- 6	- 7	-10	-15
17	-16	-12	- 8	- 9	-15	-16	-16	-11	- 9	- 8	-12	-16
18	-17	-13	-10	-10	-16	-17	-17	-12	-10	-10	-13	-17
19	-17.5	-14	-12	-12	-17	-18	-18	-13	-11.5	-11.5	-14	-17.5
20	-18	-15	-13	-13	-18	-18	-18	-15	-13	-13	-15	-18
21	-18	-16	-15	-15	-18	-18	-18	-16	-14	-14	-16	-18
22	-19	-16	-15	-15	-18	-18	-18	-16	-15	-15	-16	-18
23	-19	-17	-16	-16	-18	-19	-19	-17	-16	-16	-17	-18
24	-19	-18	-17	-17	-18	-19	-19	-17	-16	-16	-17	-18
25	-19	-18	-17	-17	-18	-19	-19	-18	-17	-17	-18	-18
26	-19	-18	-17	-17	-18	-19	-19	-18	-17	-17	-18	-19
27	-19	-18	-17	-17	-18	-19	-19	-18	-17	-17	-18	-19
28	-19	-19	-17	-17	-18	-19	-19	-18	-17	-17	-18	-19

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 2 (TOUGH WHEAT) UNDER COOLING CONDITIONS AT 11:00 A.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	70	71	72	72	71	70	70	71	72	72	71	70
2	46	66	69	68	65	46	49	67	68	68	67	52
3	31	58	66	65	56	35	38	60	66	67	63	41
4	30	51	62	61	48	31	33	53	61	63	56	36
5	19	45	57	55	41.5	19	22	46	56	57	50	26
6	9	37	51	51	33	9	12	38	50	52	43	16
7	3	28	45	42.5	25	3	5	31	44	46	35	10
8	- 1	21.5	37	35	18	- 1	0	23	36.5	39	28.5	4
9	- 4	15	30	28	12	- 4	- 3	17	29	31.5	22	0
10	- 6	10	23.5	21.5	7.5	- 6	- 5	12	22.5	25	16	- 2
11	- 8	6	18	16	4	- 7	- 7	7.5	17	19	11	- 4
12	- 9.5	2.5	12	10	1	- 8.5	- 9	3.5	11.5	13.5	7	- 6
13	-10.5	- 1	7.5	6	- 2	- 9.5	-10	0	7	9	3	- 7.5
14	-12	- 3	4	3	- 4	-10	-11	- 2	3.5	5	0	- 8.5
15	-13	- 5	0	- .5	- 6	-12	-13	- 5	0	1	- 2	-10
16	-14	- 7.5	- 2	- 3	- 8	-13	-14	- 7	- 2	- 1	- 4.5	-12
17	-15	- 10	- 5	- 6	-10	-14	-15	-10	- 5	- 5	- 8	-13
18	-16	-11	- 7	- 7	-11	-14.5	-15.5	-11	- 7	- 6	- 9	-14
19	-16.5	-12.5	- 9	- 9	-12	-15	-16	-12	- 9	- 8	-10.5	-14.5
20	-17	-13	-10	-10	-13	-15.5	-16.5	-13	-10	- 9	-11	-15
21	-17	-14	-11.5	-11.5	-14	-16	-17	-14	-11.5	-11	-12	-15.5
22	-17.5	-15	-13	-13	-14.5	-16.5	-17.5	-15	-13	-12	-13	-16
23	-18	-16	-14	-14	-15	-17	-18	-16	-14	-13	-14	-16.5
24	-18	-16	-15	-15	-16	-17	-18	-16	-15	-14	-15	-17
25	-18	-16	-15	-15	-16	-17	-18	-16	-15	-15	-16	-17
26	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
27	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
28	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 2 (TOUGH WHEAT) UNDER COOLING CONDITIONS AT 11:00 A.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	70	71	72	72	71	70	70	71	72	72	71	70
2	57	67	70	69	67	52	56	69	70	70	68	53
3	46	64	68	66	54	42	44	63	67	68	63	43
4	39	56	62	60	47	36	37	55	62	63	55	36
5	29	48	52	52	39	25	28	47	55	57	48	26
6	19	40	48	44.5	29	15	17.5	39.5	46	49	39	15.5
7	11.5	31.5	40	36	20.5	8	10	30	39	41	31	8.5
8	6	24	32	28	13.5	3	4	22	31	33	22	4
9	1.5	17	25	21	8	- 1	- 1	15	24	25	16.5	- 1
10	- 2	12	19	15	4	- 3	- 3.5	10	17.5	19.5	11	- 3
11	- 4	7	13	11	1	- 5	- 5.5	6.5	12.5	14	7.5	- 5
12	- 8	4	9	7	- 1	- 7	- 8	3	8	10	4	- 7.5
13	- 8.5	.5	5	3.5	- 3	- 8	- 9	0	5	6	0	- 9
14	- 9.5	- 2	2	1	- 5	- 9	-10	- 2.5	1	3	- 2	-10
15	-11	- 4	0	- 2	- 7	-10	-11	- 4	- 1	0	- 4	-11
16	-12	- 5.5	- 2	- 4	- 8	-11	-12	- 6	- 3	- 2	- 5	-12
17	-13	- 8	- 5	- 6	-10	-13	-13	- 8	- 5	- 4	- 8	-13
18	-14	-10	- 7	- 7	-10.5	-13.5	-14	- 9	- 7	- 6	-10	-14
19	-15	-11	- 8	- 8	-11	-14	-15	-11	- 9	- 8	-11	-15
20	-15.5	-12	- 9.5	- 9.5	-12	-14.5	-15.5	-12	-10	- 9	-12	-15.5
21	-16	-13	-11	-11	-13	-15	-16	-13	-11	-10	-13	-16
22	-16.5	-14	-12	-12	-14	-15.5	-16.5	-14	-12	-11	-14	-16.5
23	-17	-15	-13	-13	-15	-16	-17	-14.5	-13	-12	-14.5	-17
24	-17	-15	-14	-14	-15	-16	-17	-15	-14	-13	-15	-17
25	-17	-15	-14	-14	-15	-16	-17	-15	-14	-14	-15	-17
26	-17	-16	-15	-15	-16	-17	-17	-16	-15	-15	-16	-17
27	-17	-16	-15	-15	-16	-17	-17	-16	-15	-15	-16	-17
28	-17	-16	-15	-15	-16	-17	-17	-16	-15	-15	-16	-17

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 3 (TOUGH WHEAT) UNDER COOLING CONDITIONS AT 1:00 P.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	70	71	72	72	71	70	70	71	72	72	71	70
2	52	67	68	68	66	53	46	68	68	67	65	49
3	41	61	66	65	58	42	35	62	66	65	56	38
4	35	54	62	60	50	36	31	55	61	61	49	34
5	25	49	52	55	44	26	17	49	51	51	42	22
6	15	41	51	48	36	17	8	42	50	50	33	12
7	9	33	44	41.5	28	10	2.5	34	42.5	43	25	5.5
8	3.5	25.5	38	34	21	5	- 1	27	35	35	18	1
9	- .5	19	30	27	15	2	- 4	20	28	28	12	- 2
10	- 4	13.5	23.5	21	11	- 1	- 6	15	22	22	8	- 5
11	- 5.5	9	17.5	16	7	- 3	- 7	10	16	16	4	- 7
12	- 8	4.5	12	10	3	- 5.5	- 9.5	6	11	11	0	- 9
13	- 9.5	1	8	6.5	0	- 7	-11	2	7	7	- 3	-10.5
14	-11	- 2	4	3	- 3	- 9	-12	- 1	3	3	- 5	-12
15	-12	- 4	0	- 1	- 5	-11	-14	- 3	0	0	- 7	-13
16	-14	- 7	- 3	- 4	- 8	-12	-15	- 6	- 4	- 4	-10	-15
17	-15	- 9	- 5	- 6	-10	-13	-16	- 8	- 6	- 6	-11	-16
18	-15.5	-10.5	- 7.5	- 7.5	-11	-14.5	-16.5	- 9.5	- 8	- 8	-12	-16.5
19	-16	-12	- 9	- 9	-12	-15	-17	-11	- 9.5	- 9.5	-13	-17
20	-16.5	-13	-11	-11	-13	-16	-17	-12	-11	-11	-14	-17
21	-17	-14	-12	-13	-14	-16	-17	-13	-12	-12	-15	-17
22	-17.5	-15	-12.5	-14.5	-15	-17	-18	-14	-13	-13	-16	-18
23	-18	-16	-15	-15	-16	-18	-18	-15	-15	-15	-17	-18
24	-18	-16	-15	-15	-16	-18	-18	-16	-16	-16	-17	-18
25	-18	-17	-15	-15	-17	-18	-18	-17	-16	-16	-17	-18
26	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
27	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
28	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 3 (TOUGH WHEAT) UNDER COOLING CONDITIONS AT 1:00 P.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	70	71	72	72	71	70	70	71	72	72	71	70
2	62	70	70	70	69	56	61	69	70	70	69	61
3	51	64	68	67	61	44	50	64	67	68	61	50
4	43	57	63	60	53	37	43	56	62	62	53	43
5	34	49	52	53	47	28	34	49	55	55	46	34
6	25	41	48	46	37	18	24	40	47	47	36.5	24
7	16	33	40	37	28	10	16	31.5	39.5	39.5	28	16
8	10	25	32	29.5	21	5	9.5	24	31.5	31.5	20	9.5
9	5	18	25	22	14	2	5	17	24	24	14	5
10	2	13	19	17	10	- 2	2	12	18	18	9.5	2
11	- 1.5	8.5	14	12	6	- 4	- 1	8	13.5	13.5	5	- 1
12	- 4	4	9.5	8	3.5	- 6	- 4	5	8.5	8.5	2	- 4
13	- 6	1.5	6	4.5	0	- 8	- 5	1.5	5	5	- 1	- 5
14	- 8	- 1	2	1	- 2	- 9	- 7	- 1	2	2	- 2	- 7
15	- 9	- 4	0	- 1	- 4	-10	- 9	- 3	- 1	- 1	- 5	- 9
16	-10	- 6	- 4	- 4	- 7	-12	-11	- 6	- 3	- 3	- 7	-11
17	-11	- 8	- 5	- 5	- 8	-13	-12	- 7	- 4.5	- 4.5	- 9	-12
18	-12	- 9	- 6	- 6	- 9	-14	-13	- 9	- 6.5	- 6.5	-11	-13
19	-13.5	-10.5	- 8	- 8	-10.5	-14.5	-14	-10	- 8	- 8	-11.5	-14
20	-14	-11	-10	-10	-12	-15	-15	-11	-10	-10	-12	-15
21	-15	-12	-11	-11	-13	-16	-16	-12	-11	-11	-13	-16
22	-16	-13	-12	-12	-14	-17	-16.5	-13	-12	-12	-14	-16.5
23	-17	-15	-13	-13	-15	-17.5	-17	-15	-13	-13	-15	-17
24	-17	-15	-14	-14	-16	-18	-17	-15	-14	-14	-16	-17
25	-17	-16	-15	-15	-16	-18	-17	-16	-15	-15	-16	-17
26	-18	-17	-16	-16	-17	-18	-17	-16	-15	-15	-16	-17
27	-18	-17	-16	-16	-17	-18	-17	-16	-15	-15	-16	-17
28	-18	-17	-16	-16	-17	-18	-17	-16	-15	-15	-16	-17

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 4 (DRY WHEAT) UNDER COOLING CONDITIONS AT 3:00 P.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	70	70	71	71	70	70	70	70	71	71	70	70
2	44	59	62	63	62	50	40	61.5	64	64	59	49
3	33	49	55	57	53	39	31	52	59	57	49	37
4	28	44	49	51	46	33	28	44	53	51	42	32
5	14	32	40	43	37	22	13	36	46	43	33	20
6	5	22	32	35	28	11	4	27	38	35	23.5	10
7	- 1	14	25	27	20	5	- 2	19	30	27	15.5	3.5
8	- 5	8	17.5	20	13	0	- 5	12	23	20	9	- 1
9	- 8	3	11	12.5	7.5	- 3.5	- 8	6.5	16	13.5	4	- 4.5
10	-10	- 1	6	8	3	- 6	- 9	2	10	8	0	- 7
11	-12	- 4	2	4	- 1	- 8	-10	- 1	5	4	- 2.5	- 8
12	-13	- 7	- 3	- 1	- 4	-10	-11	- 5	1	0	- 6	-10
13	-13.5	- 9	- 5	- 3.5	- 6	-10.5	-12	- 6	- 2	- 3	- 7.5	-11
14	-14.5	-10	- 7	- 6	- 8	-11	-13	- 7.5	- 5	- 5.5	- 9	-12
15	-16	-12	- 9	- 8	-10	-13	-14	-10	- 7	- 8	-11	-14
16	-17	-14	-12	-10	-12	-15	-15	-12	- 9	-10	-13	-15
17	-17.5	-15	-13	-12	-13	-15.5	-15.5	-13	-11	-11	-14	-15.5
18	-18	-16	-14	13	-14	-16	-16	-14	-12	-12	-15	-16
19	-18	-16.5	-15	-14.5	-15	-16.5	-16.5	-15	-13	-13	-16	-17
20	-18	-17	-16	-15	-15.5	-17	-17	-16	-14	-14	-17	-17.5
21	-18.5	-17	-16	-16	-16	-17	-17	-16	-15	-15	-17	-18
22	-19	-18	-17	-17	-17	-18	-17.5	-17	-16	-16	-17	-18
23	-19	-18	-17	-17	-17	-18	-18	-17	-16	-16	-17	-18
24	-19	-18	-17	-17	-17	-18	-18	-17	-16	-16	-17	-18
25	-19	-18	-17	-17	-18	-18	-18	-17	-17	-17	-17	-18
26	-19	-18	-18	-18	-18	-19	-19	-18	-17	-17	-18	-19
27	-19	-18	-18	-18	-18	-19	-19	-18	-17	-17	-18	-19
28	-19	-18	-18	-18	-18	-19	-19	-18	-17	-17	-18	-19

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 4 (DRY WHEAT) UNDER COOLING CONDITIONS AT 3:00 P.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	70	70	71	71	70	70	70	70	71	71	70	70
2	56	66	70	70	69	52	48	66	70	70	68	58
3	45	57	65	67	64	41	38	56	67	65	59.5	46
4	38	49	58	61	58	36	33	49	61	59	52	39
5	28	41	51	53	50	25	20	40	53	51	44	29
6	18	31	43	46	42	15	11	30	45	43.5	34	19
7	11	22.5	34	36.5	33	8	4.5	22	36	34	26	11
8	5	15	26	29	25	3	0	20	28	25.5	18.5	6
9	1	9.5	19	22	17	- 1	- 4	9	21	19	13	2
10	- 2	5	13	15.5	12	- 3	- 5	5	15	13	8	- 1
11	- 5	1.5	8	10.5	8	- 5	- 7	2	10	8	3	- 4
12	- 7	- 3	4	6	4	- 8	- 9	- 3.5	5	4	- 1	- 8
13	- 9	- 4	.5	3	1	- 8.5	- 9.5	- 4	3	2	- 2.5	- 8.5
14	-10	- 6	- 2	0	- 2	-10	-11	- 6	- 1	- 2	- 5	-10
15	-12	- 8	- 5	- 3	- 5	-12	-12	- 9	- 3	- 5	- 7	-12
16	-14	-11	- 7	- 5	- 7	-13	-13	-10	- 6	- 7	- 9	-13
17	-14.5	-12	- 8	- 7	- 9	-14	-14	-11	- 8	- 9	-11	-14
18	-15	-13	-10	- 9	-11	-15	-15	-12	- 9.5	-10	-12.5	-15
19	-16	-14	-11.5	-10.5	-11.5	-15.5	-15.5	-13	-11	-11	-13	-16
20	-17	-15	-13	-12	-13	-16	-16	-14	-12	-12	-14	-16.5
21	-17	-16	-14	-13	-14	-16	-16	-15	-13	-13	-15	-17
22	-18	-17	-15	-14	-15	-17	-17	-16	-14	-14	-16	-17
23	-18	-17	-16	-15	-16	-17	-17	-16	-15	-15	-16	-17
24	-18	-17	-16	-15	-16	-17	-17	-16	-15	-15	-16	-17
25	-18	-17	-16	-15	-16	-17	-17	-16	-15	-15	-16	-17
26	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
27	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18
28	-18	-17	-16	-16	-17	-18	-18	-17	-16	-16	-17	-18

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 1 (DRY WHEAT) UNDER WARMING CONDITIONS AT 9:00 A.M.

DAY	THERMOCOUPLE POSITION (36 ins FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	3	-11	-12	-12	-11	- 6	4	-11	12	-12	-11	0
2	14	- 1	- 4	- 4	- 2	6	13	- 2	- 3	- 3	- 1	12
3	27	12	8	8	12	18	25	12	10	10	12	24
4	46	27	22	22	28	35	43	26	24	24	27	43
5	54	38	33	32	36	45	52	36	34	34	38	52
6	58	46	41	40	44	53	57	45	42	42	46	57
7	62	52	48	47	51	57	60	51	48	48	52	60
8	64	56	52	51	54	60	63	55	52	52	56	63
9	66	60	56	55	58	63	65	58	56	56	59	66
10	66.5	63	60	59	62	65	66	62	60	60	60	66.5
11	67	64	61	60	63	66	67	63	61	61	63	67
12	67.5	65	62	62	64	67	67	64	62	62	64	67
13	68	65.5	64	64	65	68	69	65	64	64	65	67.5
14	68.5	67	65	65	66	69	69	66	65	65	66	69
15	69	67	66	66	67	69	69	67	66	67	67	69
16	69.5	68	67	67	68	69	69	68	67	67	68	69
17	70	68	67	67	68	69	69	68	67	67	68	68
18	70.5	68	67	67	68	69	69	68	67	67	68	68
19	71	69	68	68	69	70	70	69	68	68	69	70
20	71	70	70	70	70	71	71	70	70	70	70	70
21	71	70	70	70	70	73	73	71	71	71	70	70
22	71	71	71	71	71	73	73	72	71	71	70	71
23	71	71	71	71	71	73	73	72	71	71	70	71
24	71	71	71	71	71	73	73	72	71	71	71	71
25	71	71	71	71	71	73	73	72	71	71	71	71
26	72	72	72	72	72	73.5	73	73	72	72	72	72
27	72	72	72	72	72	74	73	73	72	72	72	72
28	72	72	72	72	72	74	73	73	72	72	72	72
29	72	72	72	72	72	74	73	73	73	72	72	73
30	72	72	72	72	72	75	73	73	73	73	73	73
31	72	72	72	72	72	75	73	73	73	73	73	73
32	72	72	72	72	72	75	73	73	73	73	73	73
33	72	72	72	72	72	75	73	73	73	73	73	73
34	72	72	72	72	72	75	73	73	73	73	73	73
35	72	72	72	72	72	75	73	73	73	73	73	73

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 1 (DRY WHEAT) UNDER WARMING CONDITIONS AT 9:00 A.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN											
	13	14	15	16	17	18	19	20	21	22	23	24
1	- 5	-16	-17	-18	-16	-10	- 8	-17	-18	-18	-17	- 8
2	4	-10	-16	-16	-10	- 1	1	-14	-17	-17	-12	2
3	15	- 2	-13	-13	- 2	8	11	- 7	-13	-13	- 5	12
4	30	8	- 8	- 8	8	21	25	1	- 8	- 8	3	26
5	38	17	0	0	17	30	34	9	- 2	- 2	12	25
6	44	26	8	8	26	37	40	17	6	7	21	41
7	49	33	17	17	33	43	46	25	15	16	28	46
8	52	39	24	24	39	47	50	32	22	23	35	51
9	56	44	31	31	44	51	54	38	29	30	40	55
10	59	50	39	39	50	56	57	45	37	38	47	58
11	60	52	43	43	52	58	58	48	41	42	50	59
12	61	55	48	48	55	60	60	52	46	47	53	60
13	62	58	52	52	58	62	62	55	50	51	56	62
14	64	60	54	54	60	64	64	58	54	54	58	64
15	65	62	57	57	62	65	65	60	57	57	60	65
16	66	63	60	60	63	66	66	62	59	59	62	66
17	66	64	61	61	64	66	66	63	61	61	63	66
18	66	64	62	62	64	67	67	64	62	62	64	67
19	67	66	64	64	66	68	68	66	64	64	65	67
20	67	66	64	64	66	68	68	66	64	64	65	67
21	67	67	65	65	67	70	70	67	65	65	66	67
22	68	67	66	66	67	70	70	68	66	66	66	68
23	68	67	66	66	67	70	70	68	67	67	67	68
24	69	68	67	67	68	71	70	69	67	67	68	69
25	69	68	68	68	69	71	70	69	68	68	68	69
26	70	69	69	69	69	72	71	70	69	69	69	70
27	70	70	69	69	70	72	72	70	69	69	69	70
28	70	70	69	69	70	72	72	71	69	69	69	70
29	70	70	69	69	70	72	72	71	70	70	70	71
30	70	70	70	70	72	72	72	71	70	70	70	71
31	70	70	70	70	72	72	72	71	70	70	70	71
32	70	70	70	70	73	73	72	71	71	71	71	71
33	70	70	70	70	73	73	72	71	71	71	71	71
34	70	70	70	70	73	73	72	71	71	71	71	71
35	70	70	70	70	73	73	72	71	71	71	71	71

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 2 (TOUGH WHEAT) UNDER WARMING CONDITIONS AT 11:00 A.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0	-13	-14	-14	-12	2	- 3	-14	-14	-13	-13	- 2
2	10	- 7	-10	-10	- 4	12	7	- 7	-10	-10	- 8	8
3	25	5	- 1	- 1	8	27	21	5	- 1	- 1	2	21
4	40	15	7	7	19	41	35	14	7	6	11	35
5	47	26	16	17	29	48	44	25	16	15	21	44
6	53	35	25	26	38	53	50	34	25	24	30	50
7	57	42	33	34	44	57	55	41	33	31	38	55
8	60	48	39	40	49	60	58	47	39	38	44	58
9	63	52	44	45	53	63	61	51	44	43	48	61
10	63.5	56	50	50	57	64	63	55	50	49	53	63
11	64	58	53	53	59	64	64	58	53	52	56	64
12	64.5	60	55	55	60	64.5	64.5	59	55	55	58	64.5
13	65	61	57	57	61	65	65	60	57	57	59	65
14	66	62	59	59	62	66	66	62	59	59	61	66
15	67	64	61	61	64	67	67	63	60	60	62	67
16	67	65	62	62	65	67	67	64	62	62	63	67
17	67	66	63	63	66	67	67	65	63	63	64	67
18	67	66	64	64	66	67	67	66	64	64	65	67
19	67	66	65	65	66	67	67	66	64	64	65	67
20	67	66	65	65	66	67	67	66	65	65	65	67
21	68	68	66	66	66	67	68	67	66	65	65	68
22	69	69	67	66	66	67	69	68	67	66	66	69
23	70	70	69	67	67	68	69	69	68	67	67	70
24	71	71	70	68	68	69	70	70	69	68	68	71
25	71	72	71	69	69	70	71	71	70	70	70	71
26	73	74	73	71	70	70	72	72	71	71	72	73
27	73	75	75	72	71	70	73	74	74	74	73	73
28	73	76	76	73	72	70	73	75	75	75	74	74
29	74	77.5	78	75	72	70	73	76	76	76	75	74
30	74	79	79	76	73	70	74	77	77	78	77	75
31	74	79	81	77	74	70	74	78	79	79	78	75
32	74	79	81	77	74	70	74	78	79	80	78	75
33	74	80	82	79	74	70	74	79	80	81	80	75
34	75	80	83	80	74	70	74	79	81	82	80	75
35	75	80	83	80	74	70	74	79	81	82	80	75

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 2 (TOUGH WHEAT) UNDER WARMING CONDITIONS AT 11:00 A.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	-10	-15	-15	-15	-12	- 5	- 4	-15	-15	-15	-15	- 5
2	- 1	-12	-14	-13	- 7	3	0	-12	-13	-13	-12	5
3	9	- 6	-11	- 8	2	13	10	- 5	-11	-11	- 4	16
4	22	0	- 7	- 3	10	25	22	1	- 7	- 7	2	28
5	30	8	- 2	3	18	33	30	9	- 1	- 1	10	35
6	37	15	5	10	26	39	37	16	6	5	17	41
7	42	23	13	17	32	44	42	23	13	12	24	45
8	46	29	19	23	37	48	46	29	19	18	30	49
9	50	34	25	29	42	51	50	35	25	25	35	53
10	54	40	32	36	47	55	54	41	32	32	42	55
11	56	45	37	41	50	57	56	45	37	37	45	57
12	57	48	42	45	52	58	57	48	42	42	48	58
13	58	51	46	48	54	59	58	51	46	46	51	59
14	60	54	50	51	57	61	60	54	49	49	54	62
15	62	56	52	54	59	62	62	56	52	52	56	64
16	63	58	55	56	60	63	63	58	55	55	58	64
17	64	60	57	58	62	64	64	60	57	57	60	64
18	64	61	59	60	63	64	64	61	59	59	61	64
19	64	62	60	60	63	64	64	62	60	60	62	64
20	64	63	61	61	63	64	64	62	61	61	62	64
21	65	64	62	62	64	65	65	63	62	62	63	65
22	65	64	63	63	64	65	65	64	63	63	64	66
23	66	65	64	64	65	66	66	65	63	63	64	66
24	67	65	64	64	65	66	67	65	64	64	65	67
25	67	67	65	65	67	67	67	66	65	65	65	68
26	68	67	66	66	67	68	68	67	65	65	66	69
27	68	67	66	66	67	68	68	67	66	66	67	69
28	68	68	67	67	67	68	68	68	66	66	67	69
29	68	68	67	67	67	68	68	68	67	67	67	69
30	69	68	67	67	67	68	68	68	68	68	68	69
31	69	68	68	68	68	68	68	68	68	68	68	69
32	69	68	68	68	68	68	68	68	68	68	68	69
33	69	68	68	68	68	68	68	68	68	68	68	69
34	69	69	69	68	68	68	68	68	68	68	68	69
35	69	69	69	69	69	69	69	69	69	69	69	69

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 3 (TOUGH WHEAT) UNDER WARMING CONDITIONS AT 1:00 P.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0	-15	-15	-15	-14	- 5	1	-14	-15	-15	-14	- 1
2	6	- 9	-11	-11	- 6	5	11	- 9	-11	-11	- 5	9
3	19	2	- 3	- 1	5	18	26	2	- 2	- 2	7	22
4	32	11	6	7	15	32	40	12	6	6	18	37
5	42	22	15	17	26	41	48	22	16	16	30	45
6	49	32	24	26	35	48	53	31	25	25	38	51
7	54	40	32	34	42	53	57	39	33	33	45	56
8	57	45	39	40	47	56	60	45	39	39	50	59
9	60	50	44	45	51	60	63	49	44	44	54	62
10	63	54	50	51	56	62	64	54	50	50	58	64
11	63	57	52	53	58	63	64	56	53	53	60	64
12	64	59	55	56	60	64	65	58	55	55	61	65
13	65	60	57	58	61	65	66	60	57	57	63	67
14	66	62	59	60	63	66	67	61	59	59	64	67.5
15	67	63	61	62	64	67	67	63	61	61	65	67.5
16	67	64	62	63	65	67	67	64	62	62	66	68
17	67	65	64	64	66	67	67	65	63	63	66	68
18	67	65	64	64	66	67	67	65	64	64	66	68
19	67	66	65	65	66	67	67	66	65	65	66	68
20	67	66	65	65	66	67	67	66	65	65	66	68
21	70	68	67	67	68	69	69	67	66	66	68	71
22	71	69	68	68	69	70	70	68	68	68	69	72
23	71	70	69	69	70	70	71	69	69	69	70	72
24	72	71	71	71	71	72	72	71	70	70	71	73
25	72	72	72	72	72	72	72	72	72	72	72	73
26	73	74	74	74	74	74	74	74	73	73	74	74
27	74	75	75	75	75	75	75	76	75	74	75	75
28	74	76	77	77	77	76	75	78	77	76	76	75
29	75	78	79.5	79.5	78	76	76	80	80	79	76	75
30	76	78	81	80	79	77	76	81	80	80	77	75
31	76	80	83	83	80	77	76	82	83	81	78	75
32	76	81	84	84	81	77	76	83	84	83	79	75
33	76	82	86	86	82	78	77	85	86	84	80	75
34	77	83	87	87	83	78	77	86	87	86	80	76
35	77	83	88	88	83	78	78	86	89	87	80	76

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 3 (TOUGH WHEAT) UNDER WARMING CONDITIONS AT 1:00 P.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	-13	-15	-16	-16	-15	- 8	-11	-15	-16	-16	-15	-11
2	- 6	-14	-15	-15	-11	1	- 4	-12	-15	-15	-11	- 4
3	3	- 7	-12	- 9	- 4	11	6	- 6	-11	-11	- 4	6
4	13	- 2	- 8	- 5	2	22	16	0	- 7	- 7	2	11
5	22	5	- 2	2	10	30	25	7	- 1	- 1	10	25
6	29	12	4	9	18	37	32	15	6	6	17	32
7	35	20	11	16	25	42	38	22	13	13	25	38
8	40	26	18	23	30	47	42	28	20	20	31	42
9	44	31	24	28	36	50	47	33	26	26	36	47
10	49	38	31	35	42	53	50	40	32	32	42	50
11	52	42	36	40	46	56	53	43	37	37	45	53
12	55	46	41	45	49	58	55	47	42	42	49	55
13	56	50	45	46	52	60	57	50	46	46	52	57
14	59	53	49	51	55	61	60	53	50	50	55	60
15	61	55	52	54	57	63	61	56	53	53	57	61
16	62	58	55	57	59	64	62	58	55	55	59	62
17	63	60	57	59	60	64	63	60	57	57	60	63
18	63	60	59	60	62	65	64	61	59	59	61	64
19	64	62	61	62	63	65	64	62	61	61	63	64
20	65	63	62	62	63	65	64	62	62	62	63	64
21	66	64	63	63	64	66	65	63	63	63	65	65
22	67	65	64	64	65	66	66	64	64	64	66	66
23	68	66	65	65	65	67	67	65	65	65	67	67
24	68.5	67	66	66	66	68	67	66	65	65	67	67
25	69	67	66	66	67	68	67	67	66	66	68	67
26	69	68	67	67	68	69	68	68	67	68	69	68
27	69	68	68	68	68	69	68	68	68	68	69	68
28	70	69	68	68	68	69	68	68	68	68	69	68
29	71	70	69	69	69	70	69	69	69	69	70	69
30	71	70	69	69	69	70	69	69	69	69	70	69
31	72	71	70	70	70	70	70	70	70	70	70	70
32	72	71	70	70	70	70	70	70	70	70	70	70
33	73	72	71	70	70	70	70	70	70	71	71	70
34	74	73	72	71	70	70	70	70	71	72	72	70
35	74	73	72	71	70	70	70	70	71	72	72	70

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 4 (DRY WHEAT) UNDER WARMING CONDITIONS AT 3:00 P.M.

DAY	THERMOCOUPLE POSITION (36 ins. FROM THE BASE OF THE BIN)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1	- 8	- 9	-10	- 9	- 2	5	- 8	-10	- 9	- 8	- 1
2	13	3	0	- 2	0	9	16	2	- 2	- 1	3	11
3	28	17	13	11	13	23	31	15	10	11	17	25
4	43	29	24	23	25	36	46	27	21	22	29	40
5	52	40	34	32	35	46	53	38	30	32	39	49
6	57	47	41	40	43	53	58	45	38	40	46	54
7	60	52	47	46	49	57	61	51	45	46	52	58
8	62	56	52	51	54	60	63	55	50	51	55	61
9	65	59	55	54	57	63	66	58	53	54	59	64
10	66	62	59	58	61	66	66	61	51	58	62	66
11	66	63	60	60	62	66	66	63	59	60	63	66
12	66.5	64	62	62	63	66	66.5	64	61	61	64	66
13	67	65	63	63	64	66	67	64.5	62	62	64.5	66
14	68	66	64	64	65	67	68	65	63	63	65	67
15	68	67	65	65	66	68	68	66	65	65	66	68
16	68	67	66	66	67	68	68	67	66	66	67	68
17	68	67	66	66	67	68	68	67	66	66	67	68
18	68	67	66	66	67	68	68	67	66	66	67	68
19	68	67	66	66	67	68	68	67	66	66	67	68
20	68	67	66	66	67	68	68	67	66	66	67	68
21	68.5	68	67	67	67	68	68	67	67	67	67	68
22	69	68	67	67	67	68	69	68	67	67	67	68
23	69	69	68	68	68	69	69	69	67	67	68	69
24	70	69	68	68	68	69	70	69	68	68	69	70
25	70	69	69	69	69	69	70	69	69	69	69	70
26	70	70	70	70	70	70	70	70	70	70	70	70
27	70	70	70	70	70	70	70	70	70	70	70	70
28	70	70	70	70	70	70	70	70	70	70	70	70
29	71	70	70	70	70	70	70	70	70	70	70	70
30	71	70	70	70	70	70	70	70	70	70	70	70
31	71	70	70	70	70	70	70	70	70	70	70	70
32	71	70	70	70	70	70	70	70	70	70	70	70
33	71	70	70	70	70	70	70	70	70	70	70	70
34	71	70	70	70	70	70	70	70	70	70	70	70
35	71	70	70	70	70	70	70	70	70	70	70	70

APPENDIX I: DAILY TEMPERATURES IN °F AT VARIOUS THERMOCOUPLE POSITIONS IN BIN NO. 4 (DRY WHEAT) UNDER WARMING CONDITIONS AT 3:00 P.M.

DAY	THERMOCOUPLE POSITION (12 ins. FROM THE BASE OF THE BIN)											
	13	14	15	16	17	18	19	20	21	22	23	24
1	- 9	-15	-16	-16	-16	- 5	- 3	-10	-17	-17	-16	-10
2	0	- 9	-15	-14	-13	4	7	- 8	-15	-14	-11	- 1
3	10	- 1	- 9	-10	- 7	15	19	0	-10	- 9	- 4	10
4	22	8	- 3	- 5	- 2	26	30	8	- 5	- 3	4	21
5	31	17	5	2	7	35	38	17	2	5	13	30
6	38	25	13	10	15	40	43	25	10	13	22	37
7	43	32	21	18	22	46	48	32	18	21	29	43
8	48	38	28	25	29	50	52	38	25	28	35	47
9	52	43	34	31	35	54	55	43	31	33	40	51
10	56	48	41	39	41	56	58	48	38	40	46	55
11	57	52	46	43	46	58	59	52	43	45	50	57
12	59	54	50	48	50	60	61	54	48	49	53	59
13	60	57	52	52	53	61	62	56	51	52	55	60
14	63	59	55	54	56	63	64	59	54	55	58	63
15	64	61	58	57	58	64	65	60	57	57	60	64
16	65	62	60	59	60	65	67	62	60	60	62	65
17	65	63	61	60	61	65	67	63	61	61	63	65
18	65	64	62	62	62	66	67	64	62	62	64	65
19	65	64	63	63	63	66	67	64	63	63	64	65
20	65	65	64	64	64	66	67	64	63	63	64	65
21	66	65	64	64	64	66	67	65	64	64	64	66
22	66	65	65	64	64	66	67	65	64	64	65	66
23	67	66	66	65	65	67	67	66	65	65	65	67
24	67	66	66	66	66	67	67	66	66	66	66	67
25	68	67	67	67	67	68	68	67	67	67	67	68
26	69	68	68	68	68	69	69	68	68	68	68	69
27	69	68	68	68	68	69	69	68	68	68	68	69
28	70	69	69	69	69	69	69	68	68	68	68	69
29	70	69	69	69	69	69	69	68	68	68	68	69
30	70	69	69	69	69	69	69	68	68	68	68	69
31	70	69	69	69	69	69	69	68	68	68	68	69
32	71	71	70	69	69	69	69	68	68	68	68	69
33	71	71	70	69	69	69	69	68	68	68	68	69
34	71	71	70	69	69	69	69	68	68	68	68	69
35	71	71	70	69	69	69	69	68	68	68	68	69

APPENDIX II: FINAL MOISTURE CONTENTS IN PERCENTAGE (WET BASIS)

THERMOCOUPLE POSITION	BIN I	BIN 2	BIN 3	BIN 4
1	10.80	17.40	16.60	11.20
2	10.90	17.30	16.60	11.60
3	11.30	17.50	16.90	11.60
4	11.30	17.20	17.10	11.50
5	10.80	16.70	16.80	11.40
6	11.10	17.00	17.60	11.30
7	11.70	17.70	17.70	11.70
8	11.50	17.70	17.70	11.70
9	11.40	17.60	17.40	11.70
10	11.40	17.60	17.50	11.70
11	10.70	17.30	16.80	11.40
12	10.40	17.20	16.60	11.70
13	10.80	16.45	16.40	10.70
14	11.20	16.40	16.20	10.70
15	11.60	16.20	16.40	10.80
16	11.10	16.40	16.80	10.90
17	11.10	16.40	16.70	11.00
18	11.00	16.20	16.70	11.00
19	10.90	16.75	16.70	10.80
20	10.90	16.60	16.65	10.70
21	11.00	16.00	16.20	10.35
22	10.40	16.00	16.95	10.25
23	10.70	16.40	16.90	10.35
24	10.80	16.25	16.60	10.40

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 1

36 ins. FROM BASE OF BIN

Thermocouple Position	1	2	3	4	5	6	7	8	9	10	11	12
Temperature °F	72	72	72	72	72	75	73	73	73	73	73	73
Moisture %	10.80	10.90	11.30	11.30	10.80	11.10	11.70	11.50	11.40	11.40	10.70	10.40
% Wheat Infested												
Penicillium	18	18	16	23	12	54	20	32	35	28	38	16
Asperigillus	3	6	5	1	0	1	0	0	0	0	2	2
Alternaria	18	10	20	23	20	19	21	13	8	13	11	11
Fusarium	83	83	83	77	50	50	52	31	27	36	28	35
Mucor	3	0	0	0	2	0	2	0	4	0	0	0
Rhizopus	0	0	0	0	8	10	0	9	5	5	0	9
Circinella	0	0	0	0	0	0	0	0	0	0	0	0
% Germination	← 70 - 75 →											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 1

12 ins. FROM BASE OF BIN

Thermocouple Position	13	14	15	16	17	18	19	20	21	22	23	24
Temperature °F	70	70	70	70	73	73	72	71	71	71	71	71
Moisture %	10.80	11.20	11.60	11.10	11.10	11.00	10.90	10.90	11.00	10.40	10.70	10.80
% Wheat Infested												
Penicillium	18	3	2	10	8	6	5	9	15	7	9	11
Aspergillus	0	1	1	0	0	1	0	0	0	0	5	0
Alternaria	10	13	24	29	16	16	24	25	23	13	27	24
Fusarium	37	38	54	49	51	49	43	66	44	60	40	44
Mucor	0	4	0	0	5	0	0	5	2	2	0	0
Rhizopus	2	5	9	3	0	6	7	4	1	0	0	0
Circinella	0	0	0	0	0	0	0	0	0	0	0	0
% Germination	75%											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 2

36 ins FROM BASE OF BIN

Thermocouple Position	1	2	3	4	5	6	7	8	9	10	11	12
Temperature °F	75	80	83	80	74	70	74	79	81	82	80	75
Moisture %	17.40	17.30	17.50	17.20	16.70	17.00	17.70	17.70	17.60	17.60	17.30	17.20
% Wheat Infested												
Penicillium	72	100	100	99	97	100	98	100	100	100	96	100
Aspergillus	0	0	0	0	0	0	21	18	26	23	34	16
Alternaria	2	0	0	1	5	3	2	0	0	1	0	0
Fusarium	8	12	5	9	13	12	4	9	5	10	10	4
Mucor	0	0	0	2	0	0	0	0	0	0	0	0
Rhizopus	0	0	0	0	0	0	0	0	0	0	0	0
Circinella	25	14	7	16	4	4	4	23	16	24	15	30
% Germination	← 0 →											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 2

12 ins. FROM BASE OF BIN

Thermocouple Position	13	14	15	16	17	18	19	20	21	22	23	24
Temperature °F	69	69	69	69	69	69	69	69	69	69	69	69
Moisture %	16.45	16.40	16.20	16.40	16.40	16.20	16.75	16.60	16.00	16.00	16.40	16.25
% Wheat Infested												
Penicillium	51	54	10	12	10	5	6	3	3	12	9	13
Aspergillus	25	29	42	28	35	13	18	29	29	36	58	33
Alternaria	4	4	1	6	0	3	5	4	4	3	1	3
Fusarium	24	24	17	16	31	50	32	27	31	31	26	46
Mucor	0	0	0	0	0	0	0	0	0	0	0	0
Rhizopus	0	0	0	7	0	0	0	0	0	0	0	0
Circinella	8	4	12	5	11	7	13	11	12	5	11	3
% Germination	←					50						→

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 3

36 ins. FROM BASE OF BIN

Thermocouple Position	1	2	3	4	5	6	7	8	9	10	11	12
Temperature °F	77	83	88	88	83	78	78	86	89	87	80	76
Moisture %	16.60	16.60	16.90	17.10	16.80	17.60	17.70	17.70	17.40	17.50	16.80	16.60
% Wheat Infested												
Penicillium	0	1	10	9	3	3	96	100	100	100	96	85
Aspergillus	100	100	100	100	99	99	0	1	6	1	22	0
Alternaria	0	0	0	0	2	0	6	1	0	0	1	11
Fusarium	10	11	4	7	5	11	5	2	3	5	14	40
Mucor	0	0	0	0	0	0	29	31	26	19	6	7
Rhizopus	0	0	0	0	0	0	0	0	0	0	0	0
Circinella	9	2	3	11	13	12	0	0	0	0	0	0
% Germination	← 0 - 25 →											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 3

12 ins. FROM BASE OF BIN

Thermocouple Position	13	14	15	16	17	18	19	20	21	22	23	24
Temperature °F	74	73	72	71	70	70	70	70	71	72	72	70
Moisture %	16.40	16.20	16.40	16.80	16.70	16.70	16.70	16.65	16.20	16.95	16.90	16.60
% Wheat Infested												
Penicillium	17	11	2	5	7	9	4	7	1	5	3	7
Aspergillus	0	0	0	23	1	4	1	0	0	2	2	0
Alternaria	14	11	17	26	21	21	34	21	31	29	25	31
Fusarium	43	47	71	68	60	56	52	58	51	50	54	48
Mucor	18	19	13	6	7	0	0	0	21	13	0	6
Rhizopus	0	0	0	0	0	0	0	0	0	0	0	0
Circinella	0	0	0	0	0	0	0	0	0	0	0	0
% Germination	75											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 4

36 ins. FROM BASE OF BIN

Thermocouple Position	1	2	3	4	5	6	7	8	9	10	11	12
Temperature °F	71	70	70	70	70	70	70	70	70	70	70	70
Moisture %	11.20	11.60	11.60	11.50	11.40	11.30	11.70	11.70	11.70	11.70	11.40	11.70
% Wheat Infested												
Penicillium	3	12	1	4	4	2	0	0	2	0	1	3
Aspergillus	0	0	3	0	0	0	0	0	0	0	0	0
Alternaria	30	23	25	22	20	23	32	32	32	26	36	42
Fusarium	43	61	62	63	65	60	78	66	75	71	53	53
Mucor	0	0	0	2	0	3	0	0	0	0	0	0
Rhizopus	0	0	0	0	4	2	0	5	0	0	0	0
Circinella	0	0	0	0	0	0	0	0	0	0	0	0
% Germination	← 80 - 89 →											

APPENDIX III: RESULTS FROM MICROBIAL ANALYSIS BIN 4

12 ins FROM BASE OF BIN

Thermocouple Position	13	14	15	16	17	18	19	20	21	22	23	24
Temperature °F	71	71	70	69	69	69	69	68	68	68	68	69
Moisture %	10.70	10.70	10.80	10.90	11.00	11.00	10.80	10.70	10.35	10.25	10.35	10.40
% Wheat Infested												
Penicillium	2	2	1	1	0	1	2	1	1	0	1	1
Aspergillus	0	0	0	0	0	0	0	0	0	0	0	0
Alternaria	26	27	32	27	30	26	28	28	34	32	23	31
Fusarium	65	66	71	77	68	66	75	71	64	61	61	81
Mucor	0	0	0	1	0	0	0	0	0	0	0	0
Rhizopus	2	0	0	0	0	2	0	0	4	0	0	0
Circinella	0	0	0	0	0	0	0	0	0	0	0	0
% Germination	← 80 - 89 →											